Photovoltaic Equipment

International Technology Roadmap for Photovoltaic (ITRPV)

2021 Results

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Results 2021

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Content

1. Executive Summary

The photovoltaic (PV) industry needs to provide power generation products that can compete with both, conventional energy sources and other renewable sources of energy. An international technology roadmap can help to identify trends and to define requirements for any necessary improvements. The aim of the International Technology Roadmap for Photovoltaic (ITRPV) is to inform suppliers and customers about anticipated technology trends in the crystalline silicon (c-Si) based photovoltaic industry and to stimulate discussions on required improvements and standards. The objective of the roadmap is not to recommend detailed technical solutions for identified areas which need improvement, but instead to emphasize to the PV community the need for improvement, to formulate requirements to meet and to encourage in this way the development of comprehensive solutions. The present, thirteenth edition of the ITRPV was jointly prepared by 62 leading international poly-Si producers, wafer suppliers, c-Si solar cell manufacturers, module manufacturers, PV equipment suppliers, and production material providers, as well as PV research institutes and consultants. The present publication covers the entire c-Si PV value chain from crystallization, wafering, cell manufacturing to module manufacturing, and PV systems. Significant parameters set out in earlier editions are reviewed along with several new ones, outdated parameters were omitted and discussions about emerging trends in the PV industry are reported.

The global c-Si cell and PV module production capacity at the end of 2021 is assumed to have further increased to over 470 GWp due to continued capacity expansions [1]; the market share of about 95% for the c-Si and about 5% for thin-film technologies is assumed to be unchanged [2].

The PV module market in 2021 showed a significant growth to 183 GW. This growth was realized despite challenges in poly-Si supply, logistics and material supply [3,4,5,6].

The c-Si module market shift to mono-Si continued in parallel with the implementation of innumerable module products deploying more and more M10, and M12 wafer formats together with bifacial module technology. The weighted average price of c-Si modules increased in 2021 by about 10% compared to the end of 2020, close to 15% without including annual inflation [7]. Mono-Si based products experienced a significant price increase while price premiums for bifacial and high-power modules nearly disappeared at the end of 2021. Spot market price for PV modules has increased for the first time since more than 10 years by about 10%. End users outside China have had to bear further burden in the range of 2 to 4 $ct/Wp due to tremendous increased logistic prices for container shipments from Asia to the world [8, 9]. The reduced competitiveness of mc-Si based products resulted in a further market share reduction to 13%.

Efficiency improvements in PERC technology and the deployment of larger wafers in larger module resulted in higher average module efficiencies. The use of larger wafers enabled new module power classes of 600 W and above. PV manufacturers continued in 2021 the installation of new PERC cell and module production capacities, capable for the new cell formats. They also invested in the upgrade of existing production lines to increase cell efficiencies and to enable the use the new wafer formats. The price experience curve continued with its historic learning and the learning rate (LR) was calculated to 24.1 %. The PV industry can keep the LR up over the next years by continuing the proofed combination of cost reduction measures and implementation of cell perfections, with improved wafer material, improved cell front and rear sides, refined layouts, introduction of bifacial cell concepts, improved module technologies as well as with the introduction of new cell technologies. The introduction of larger cell formats contributes to PV system cost reduction. Improvements in all fields will result in module area efficiency increase: today's mainstream p-type mono-Si based modules reach efficiencies of 21% that will increase to 22.5% within the next 10 years, n-type based modules including Heterojunction (SHJ) provide highest power modules with today's efficiencies of close to 22% that will

increase up to 24% within the next 10 years. Si-based Tandem cells and modules are expected in mass production around 2026, starting with module efficiencies of 26%. The combination of optimized manufacturing costs and increased cell and module performance will support the reduction of PV system costs and thus ensure the long-term competitiveness of PV power generation. All aspects are again discussed in this revision of the ITRPV.

VDMA continues the roadmap activity, and updated information will be published annually to ensure comprehensive communication between manufacturers and suppliers throughout the value chain. More information is available at itrpv.vdma.org.

2. Approach

The main c-Si technology value chain elements wafer, cell, and module are discussed in three areas: materials, processes, and products. Data was collected from the participating companies and processed anonymously by VDMA. The participating companies jointly agreed that the results are reported in this roadmap publication. All plotted data points of the parameters reported are median values generated from the input data. Beside the discussion of parameters linked to crystallization, wafers, cells, modules, we look at the impact and trends for PV systems and discuss trends in smart fab manufacturing.

2.1. Materials

The requirements and trends concerning raw materials and consumables used for wafer, cell, and module manufacturing are described in these subsections. Reducing the consumption or substitution of some materials will be necessary in order to ensure availability, avoid environmental risks, reduce costs, and increase efficiency. Price development plays a major role in making PV-generated electricity competitive with other renewable and fossil sources of energy.

2.2. Processes

New technologies, new materials, and highly productive manufacturing equipment are required to reduce production costs. By providing information on key production technologies and by discussing process parameters to optimize the wafer production, to increase cell and module efficiency as well as module power output, this roadmap constitutes a guide to new developments and aims to support their progress. The subsections on processes identify manufacturing and technology issues for each segment of the value chain. Manufacturing topics center on raising productivity, while technological developments aim to ensure higher cell and module efficiencies.

2.3. Products

Each PV value chain element contributes to final products. The products subsections therefore discuss the anticipated development of the value chain elements ingot, wafer, c-Si solar cell, and module over the coming years.

3. PV Learning Curve

It is obvious that cost reductions in PV production processes will also result in price reductions [10]. Fig. 1 shows the price experience curve for PV modules, displaying the average module sales prices - at the end of the corresponding period - (in 2021 US$/Wp) as a function of cumulative module shipments from 1976 to 12/2021 (in MWp) [10, 11, 12]. Displayed on a log-log scale, the plot changes to an approximately linear line until the shipment value of 3.1 GWp (shipments at the end of 2003), despite bends at around 100 MWp. This indicates that for every doubling of cumulative PV module shipment, the average selling price decreases according to the learning rate (LR). Considering all data points from 1976 until 2021 we found an LR of about 24.1% - again a slight increase compared to the 23.8% in the 12th edition. The large deviations from this LR plot in Fig. 1 are caused by market fluctuations between 2003 and 2012 as well as in 2016 and 2018.

Learning curve for module price as a function of cumulative shipments

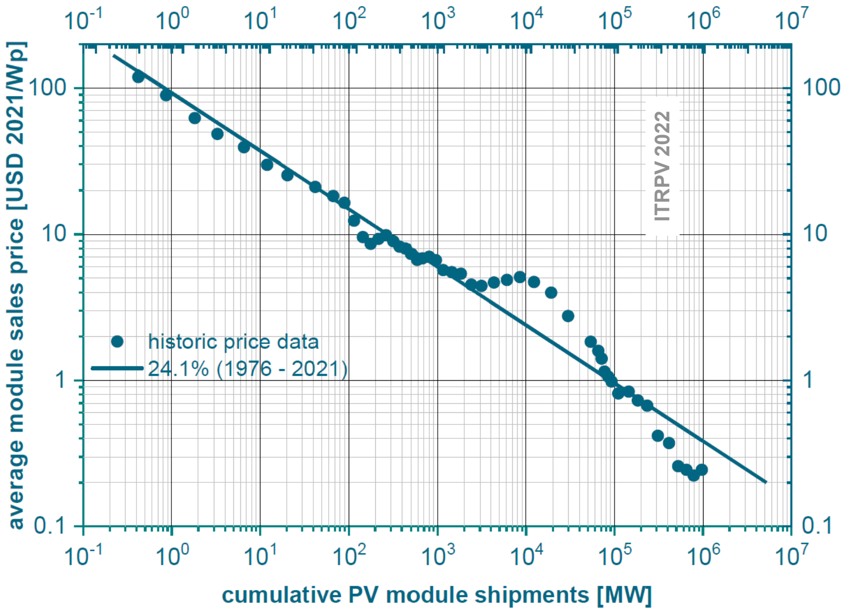


Fig. 1: Learning curve for module spot market price as a function of cumulative PV module shipments.

The last data point indicates the module shipment volume and average spot market price at the end of 2021. The 2021 shipment volume is calculated to 183 GWp - Installation of 173GWp [11] plus 10 GWp in warehouses and in transit until year end 2021. Based on this data the cumulated shipped module power at the end of 2021 is calculated to approximately 972 GWp. The resulting worldwide installed cumulated module power is calculated to 940 GWp end of 2021 after 756 GWp in 2020 [12]. The corresponding average module spot market price at the end of 2021 is calculated to 0.24 US$/Wp as described in chapter 4.

4. Cost Consideration

Fig. 2 shows the price development of mono-Si modules from December 2015 to December 2021 with separate price trends for poly-Si, mono-Si wafers, cells (≤ M6, > M6, avg.), and modules [13].

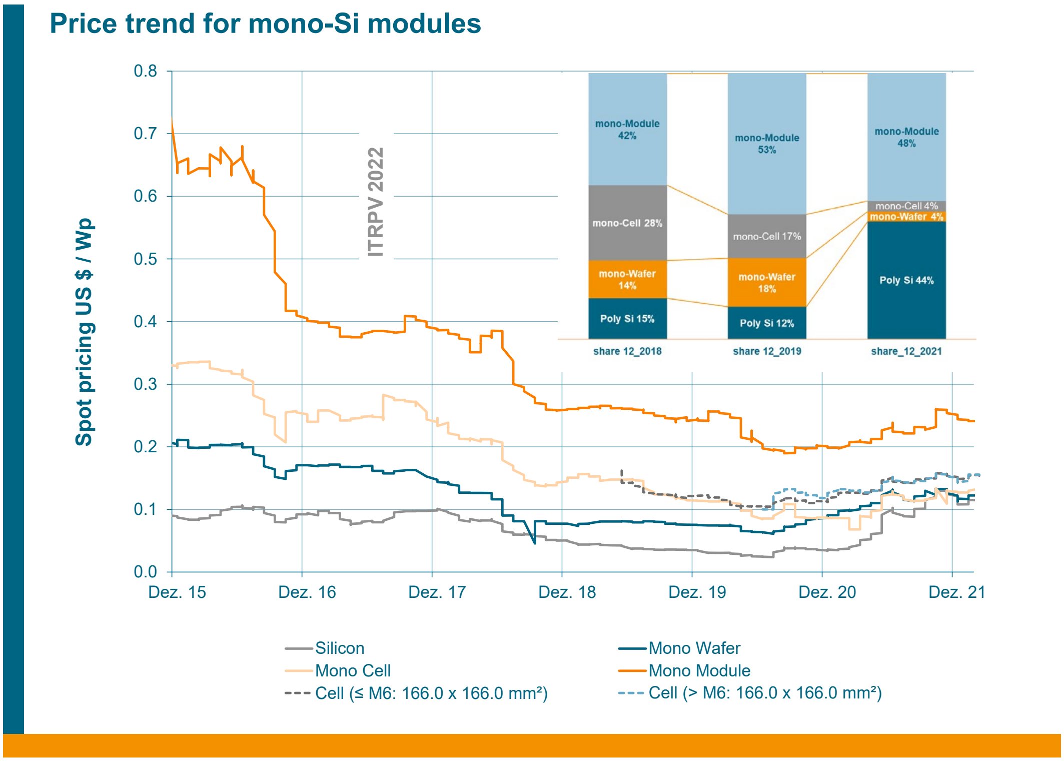


Fig. 2: Spot market price trends for poly-Si, mono-Si wafers, cells, and modules (assumption 12/2021: 2.3 g poly-Si/W (Fig. 4), average mono-Si cell efficiency 23.0%, (M6: 6.4 Wp); inset: comparison of the proportion of the price attributable to different cost elements between 12/2018, 12/2019, and 12/2021 (0.26, 0.24, and 0.24 US$/Wp) [13].

Module production capacity at the end of 2021 is assumed to exceed 470 GWp due to continued capacity expansions [1, 3]. The spot market price for standard mono-Si and mc-Si modules respectively increased during 2021 mainly due to the price soar of poly-Si [3]. The market share of mc-Si modules shrank further despite lower prices compared to mono-Si products. This situation emphasizes the continued transition to mono-Si.

Since end of 2020, publicly available price data have been reporting in addition to mono-Si and mc-Si standard module prices, also prices for cells and modules with M6, M10, and G12 wafer formats as well as for bifacial modules. Therefore, average module prices reported in Fig. 1 are calculated as weighted average of 4 different product groups: standard mc-Si modules, standard mono-Si modules, mono-Si modules with large wafer formats, and bifacial mono-Si modules.

This average module prices for 12/2021 are calculated: 0.223US$/Wp for mc-Si modules, 0.244 US$/Wp mono-Si modules, 0.25 US$/W for modules with large wafer formats as well as for bifacial modules [13, 15]. We calculated 0.244 US$/Wp as weighted average spot market price of c-Si modules at year end of 2021 based on 2021 ITRPV findings in Fig. 9, Fig. 10, and Fig. 57 The assumed market shares are therefore: 48% for standard mono-Si modules, and 39% for bifacial, high power/ large wafer-based modules, and 13% for mc- wafer based modules.

The inset of Fig. 2 shows the comparison of the proportion of prices attributable to silicon, wafer, cell, and module price for December 2018, December 2019, and December 2021. The overall price level for modules increased last year by about 10%. Main reason was the tremendous price increase of poly-Si caused by capacity shortages [3]. Soaring wafer prices had to be absorbed by cell and module manufacturers.

The non-silicon module manufacturing costs are mainly driven by consumables and materials as discussed in the c-Si PV module cost analysis in the 3rd edition of the ITRPV. Those prizes also increased significantly in 2021 and the situation is not expected to change fast. Achieving cost reductions in consumables and pre-cursor materials will be more difficult but must be continued. Improving productivity and product performance will stay in the focus resulting in continued pressure on existing and new installed manufacturing lines [16].

The known three strategies, emphasized in former ITRPV editions help to address this challenge:

- Improve module area efficiency without significantly increasing the processing cost.

- Continue the cost optimization per piece along the entire value chain by increasing the Overall Equipment Efficiency (OEE) of the installed production capacity, by implementing upgrades and new production capacities, by using Si and non-Si materials more efficiently, and ensuring higher OEE of new installed capacities.

- Introduce specialized module products for different market applications (i.e., tradeoff between cost-optimized, highest volume products and highest efficiency, higher price roof-top applications or even fully customized niche products).

The first point implies that continues cell efficiency improvements need to be implemented not only with the new, larger wafer formats but in parallel with new module concepts to further improve the module area efficiency. To enable cost efficient manufacturing this must be implemented with lean processes to optimize capital expenditures. It will remain difficult to introduce new, immature technologies that do not show reductions of the cost per Wp from the beginning.

5. Results of 2021 | Crystallization and Wafering

5.1. Materials

Poly-Si remains the most expensive material of a c-Si solar cell as discussed in chapter 4. Siemens process will keep today's mainstream position. FBR (Fluidized Bed Reactor) process will remain the 2nd technology of choice to produce poly-Si today. We assume the market share of FBR poly-Si to about 5% in 2021, this is close to the analysis in [17]. We expect that this share will increase to about 20% within the next 10 years against the well matured and further optimizing Siemens process. Other technologies like umg-Si (upgraded metallurgical grade-Si) are not expected to yield significant cost advantages compared to the two matured poly-Si technologies over the coming years but are expected to stay available in the market.

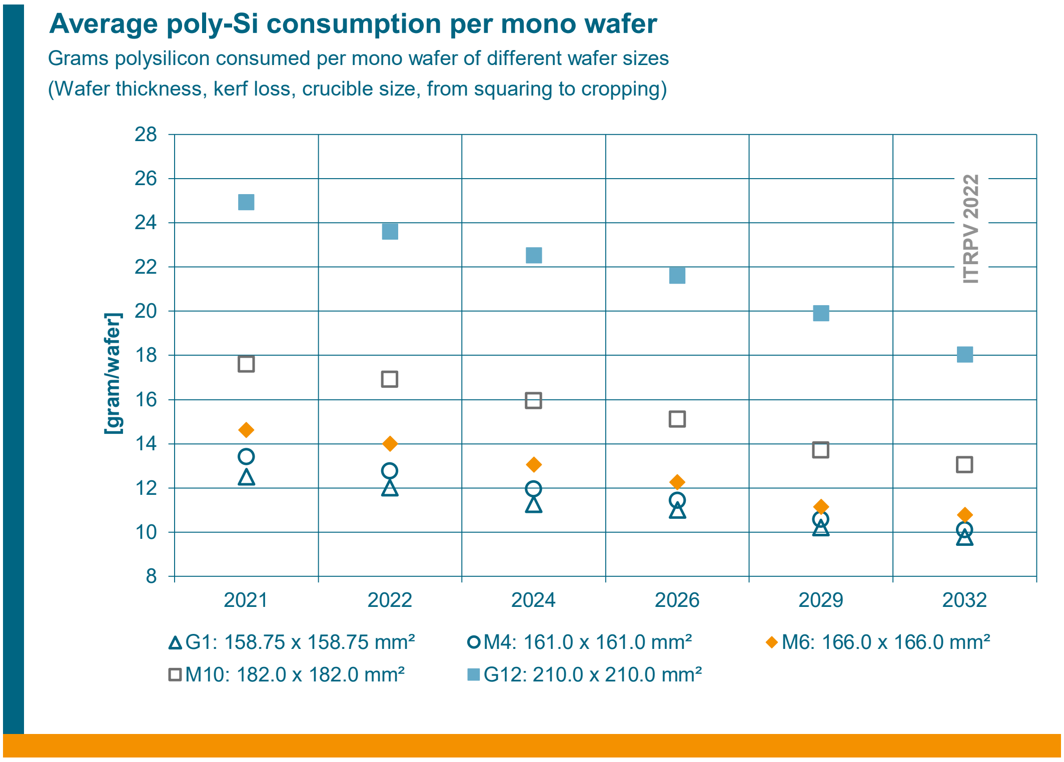


Fig. 3: Average poly-Si consumption for mono-Si wafers with diamond wafer sawing technology.

Fig. 3 shows the average utilization of poly-Si to produce silicon wafers. The weight of a 165 µm thick 166 mm x 166 mm mono-Si wafer is ≈ 10.4 g. That means 14 g or 135% of remaining Si in the wafer are necessary n 2022 to produce a standard M6 mono-Si wafer. All wafer formats will consume significant less silicon within the next 10 years. Expected reductions are in the range of 25% for M6 and 30% for M10 and G12 respectively. This reduction has to be realized by improving the yields in crystallization and wafering, by further reduction of kerf loss, and, most important, by further thickness reduction as shown in Fig. 6 to Fig. 8.

Fig. 4 shows the relative poly-Si consumption per Wp for p-type PERC wafers of the corresponding wafer sizes. Cell power is calculated according to cell efficiency trend for PERC in Fig. 34. The trend in Fig. 4 shows that, based on current assumptions, M10 and G12 format not automatically consume to a relatively lesser extend poly-Si per wafer. This emphasizes the need for even faster improvements for the larger formats in order to realize their benefits in LCOE reduction not primal on power plant level but also in further module cost reductions by more efficient use of poly-Si.

5.2. Processes

5.2.1. Crystallization

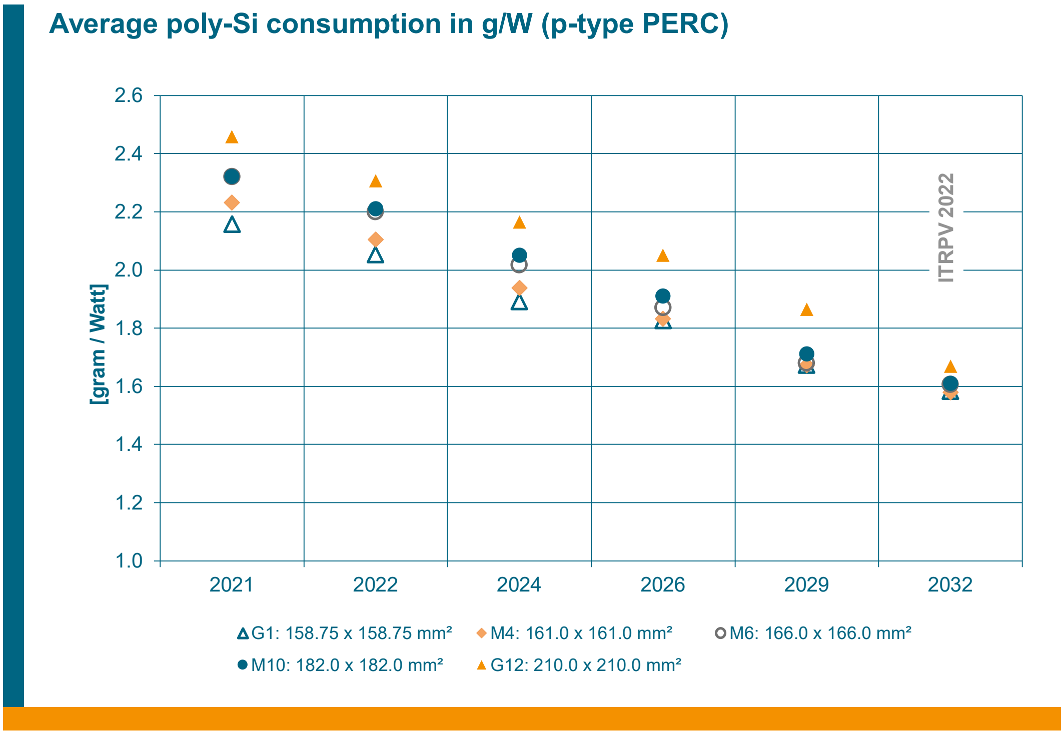


Fig. 4: Average poly-Si consumption for mono-Si wafers with diamond wafer sawing technology.

It is possible to increase the throughput of the crystallization process by changing the common sizes of the ingots and by growing more crystals with the same crucible. The trends to larger ingot mass as discussed in former ITRPV editions continue. For Czochralski (Cz) growth is a maximum possible mass of about 850kg expected that will be reached within the next 10 years.

The mainstream doping element for p-type mono-Si material is Gallium. Fig. 5 shows the market share of doping materials for p-type mono-Si. We see that boron is disappearing as doping element and the replacement by gallium will be completed soon. The biggest advantage of gallium doping is the significant reduction of Light Induced Degradation (LID) of p-type material [18].

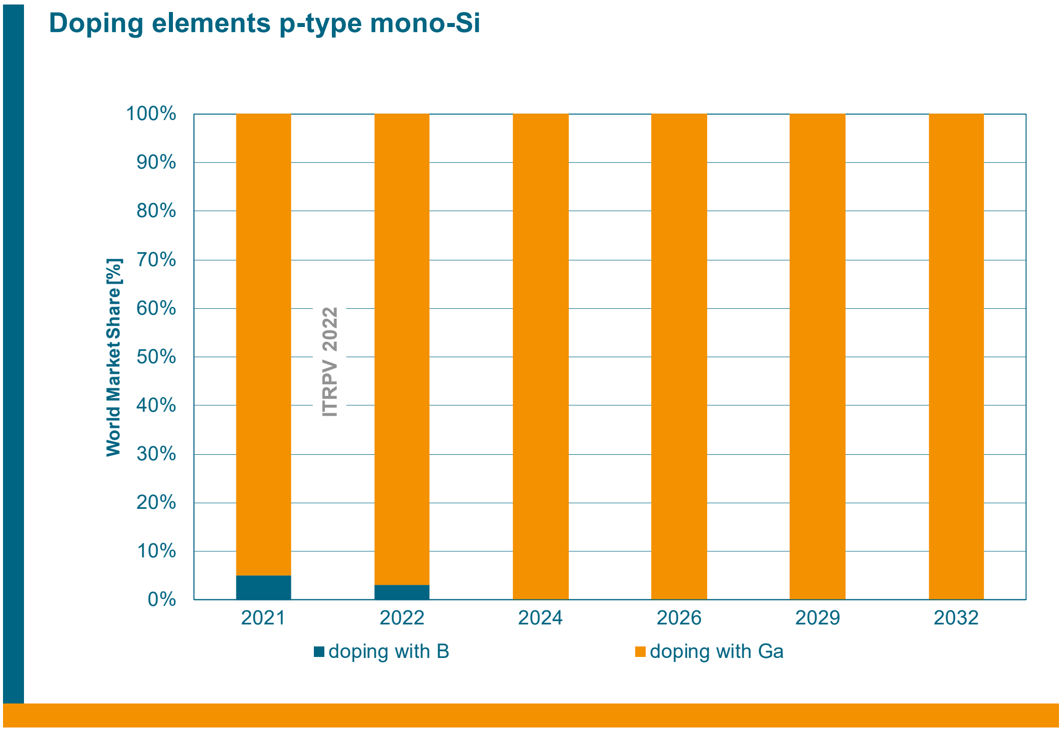


Fig.5: Expected market share of elements used for doping of p-type mono-Si material.

5.2.2. Wafering

The landscape in wafering technology changed completely during the last years. The introduction of diamond wire sawing (DWS), completed in 2018 for mono-Si and mc-Si wafering, was a significant improvement in terms of wafering process stability and cost reduction. Since its introduction, DWS has enabled significant reductions of the kerf width and contributed therefore to the improved usage of poly-Si, as discussed in chapter 5.1.

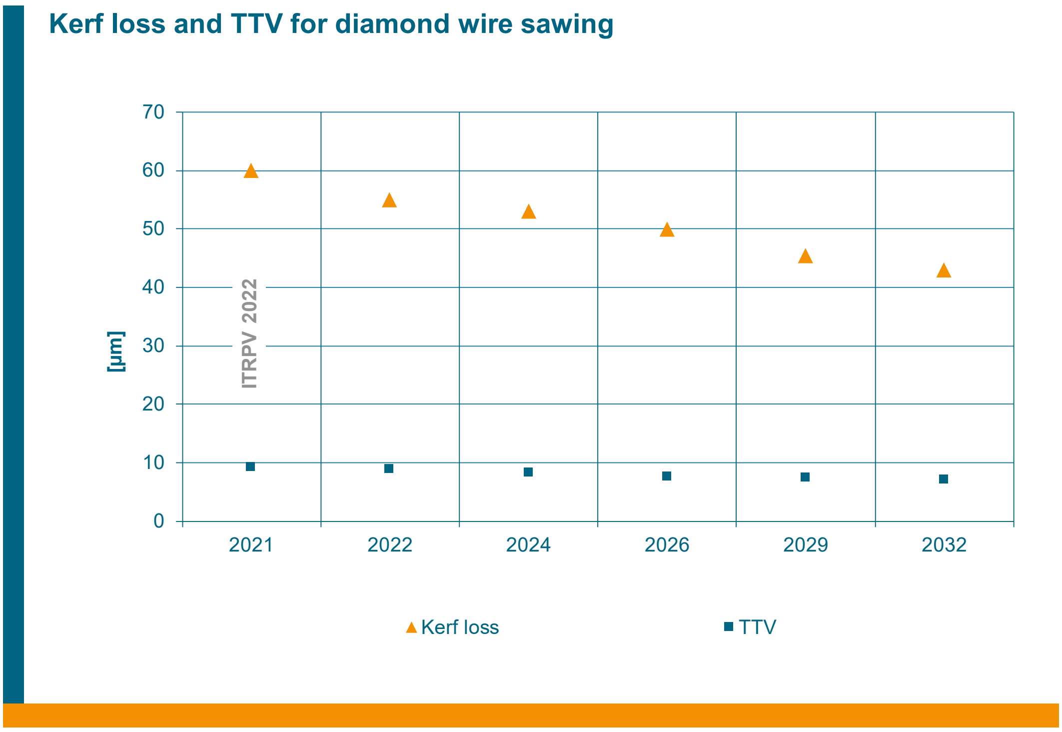


Fig. 6: Kerf loss and Total Thickness Variation (TTV) trend for diamond wire sawing of all wafer formats.

The shift was enabled by the fast improvement of appropriate wet chemical processes for saw damage removal and texturing. Kerfless wafering technologies are not expected to contribute significantly to the future PV wafer market due to the maturity of DWS. Fig. 6 describes the trend for kerf loss and for Total Thickness Variation (TTV) for all wafer sizes. A kerf width of about 60 µm is standard today in diamond wire sawing (DWS). This is in line with the request of the 12th edition. Large wafer formats benefit from this trend particularly. The kerf loss is predicted to decline to below 50 µm within the next 10 years. TTV of 10 µm is reached by today, and this is ahead of former predictions.

5.2.3. Process Improvement Trends

Thinner wafers, reducing kerf loss, increasing recycling rates, and reducing the cost of consumables, will yield in cost savings. Wire diameters will be reduced continuously and there will be more recycling of silicon and diamond wire over the next years. Increased tool throughput will improve the productivity in crystallization and wafering on top of the yield enhancements by reduced kerf loss. This contributes to further cost optimization. All technologies are expected to realize between 10% and 30% throughput increase within the next 10 years.

5.3. Products

Using poly-Si as efficient as possible has been key for further cost reduction for c-Si cells and modules especially since 2021 when poly-Si run short at exorbitant prices. Reducing the as-cut wafer thickness is now becoming the method of choice to continue cost savings.

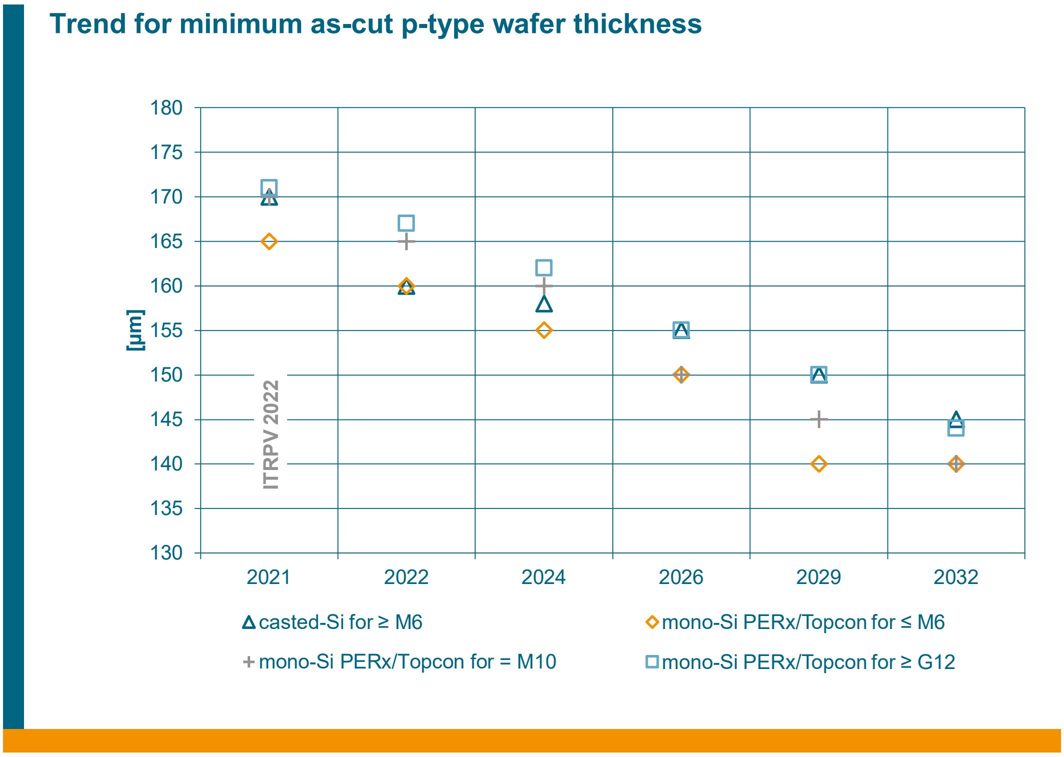


Fig. 7: Predicted trend for minimum as-cut wafer thickness of p-type c-Si wafers with different dimensions.

Fig. 7 and Fig. 8 show the expected trend for minimum as cut wafer thickness for different c-Si wafer materials and wafer sizes. Since years of stagnating wafer thickness, we have been seeing since 2020 that mono-Si wafer thickness reduction is making progress, even ahead of the trend shown in the 12th edition. 165 µm were standard in 2021 for p-type mono wafers with ≤ M6 wafer dimension. M6 wafers are expected to get a faster thickness reduction. A minimum wafer thickness of 140 µm will be

reached for M6 in 2029 and for M10 within the next 10 years as sown in Fig. 7. Mono-Si wafers ≥G12 wafers are between 5 µm and 7.5 µm thicker than mono-Si wafers in today's dominating M6 format. The corresponding cell thickness limit trend in module technology is discussed in chapter 7.

Fig. 8 shows the anticipated trend of as-cut wafer thickness for n-type mono-Si technologies with the corresponding wafer formats. Current wafer thickness for ≤ M6 wafer size is 160 µm with an expected reduction trend to below 120 µm for SHJ wafers. For larger wafers we see a trend similar to p-type wafers: minimum thickness in 2022 will be between 5 and 10µm higher for M10 and G12 wafer formats, respectively. In 2022 we expect about 5 to 10µm lower thickness for all formats compared to the corresponding p-type wafers. Minimum thickness within the next 10 years will reach values around 130 µm. M6 format will lead the thickness reduction.

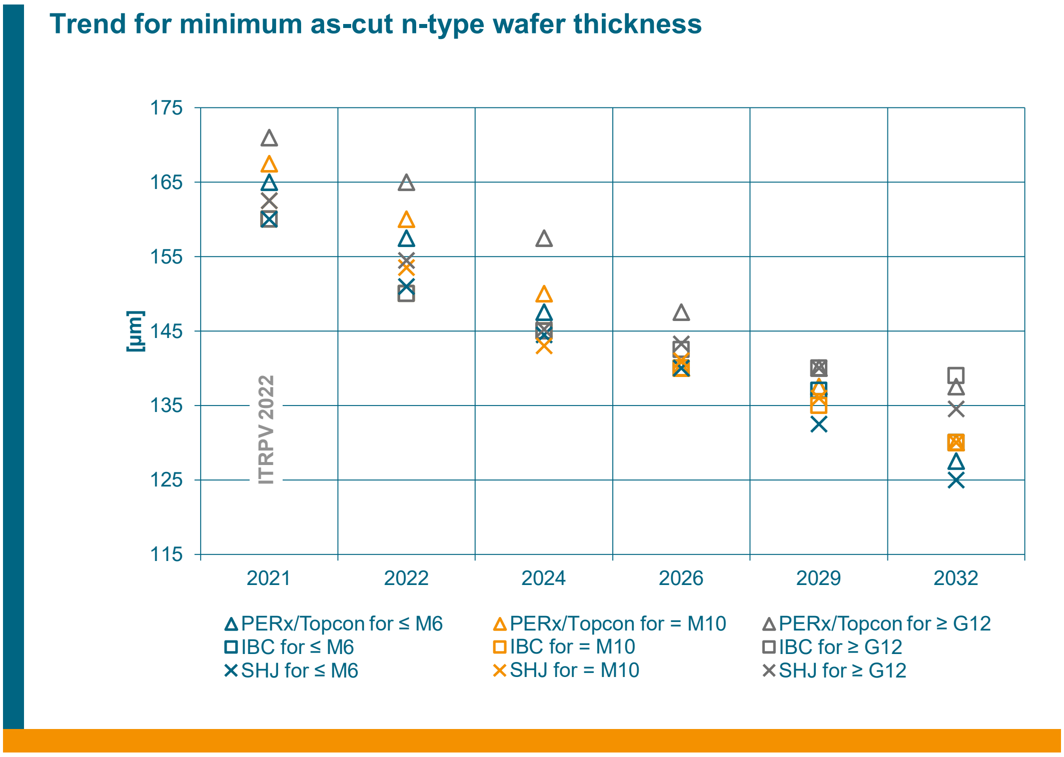


Fig. 8: Predicted trend for minimum as-cut wafer thickness n-type c-Si wafers with different wafer sizes.

Fig. 9 shows the expected market trend for different wafer types. Cz-mono-Si is clearly dominating the market. In 2021, Cz-mono-Si materials had a market share of about 87% vs. about 13% for cast-Si materials. The trend of increased Cz-mono-Si market share is in line with the assumptions of previous ITRPV editions. The plotted prediction of IHS Markit for 2021 shows that the ITRPV result is close to it [19]. The mono-Si market splits into n- and p-type. P-type, the current mainstream, is expected to stay dominant at least for the next 5 years. N-type mono-Si market share is expected to grow to 70% until 2032. Casted Si is expected to disappear until 2032.

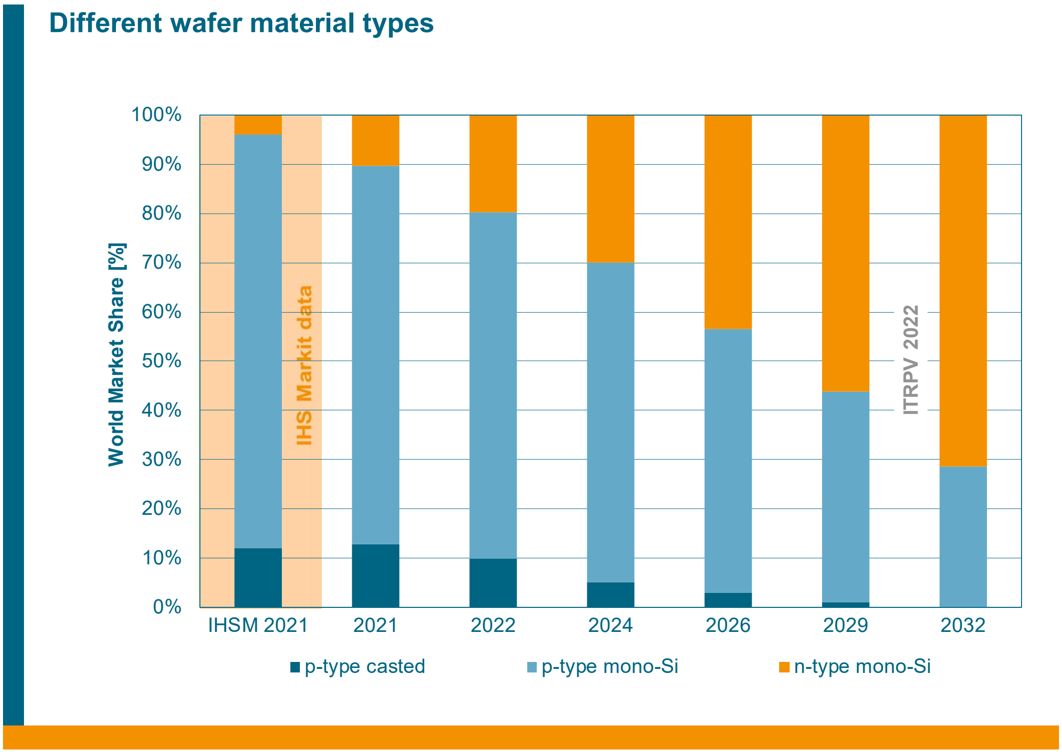


Fig. 9: Market share for different wafer types. IHS Markit data are indicated for 2021 as reference, [19].

Fig. 10 shows the share of different dimensions for mono wafers. Wafer formats ≤ M6 are losing market share. M10 and G12 formats are expected to become dominating in the market from 2022 onwards. It is still not clear yet, which of the two formats will become mainstream in future as both have advantages and disadvantages [20, 21]. So new built cell lines will be ready for both formats.

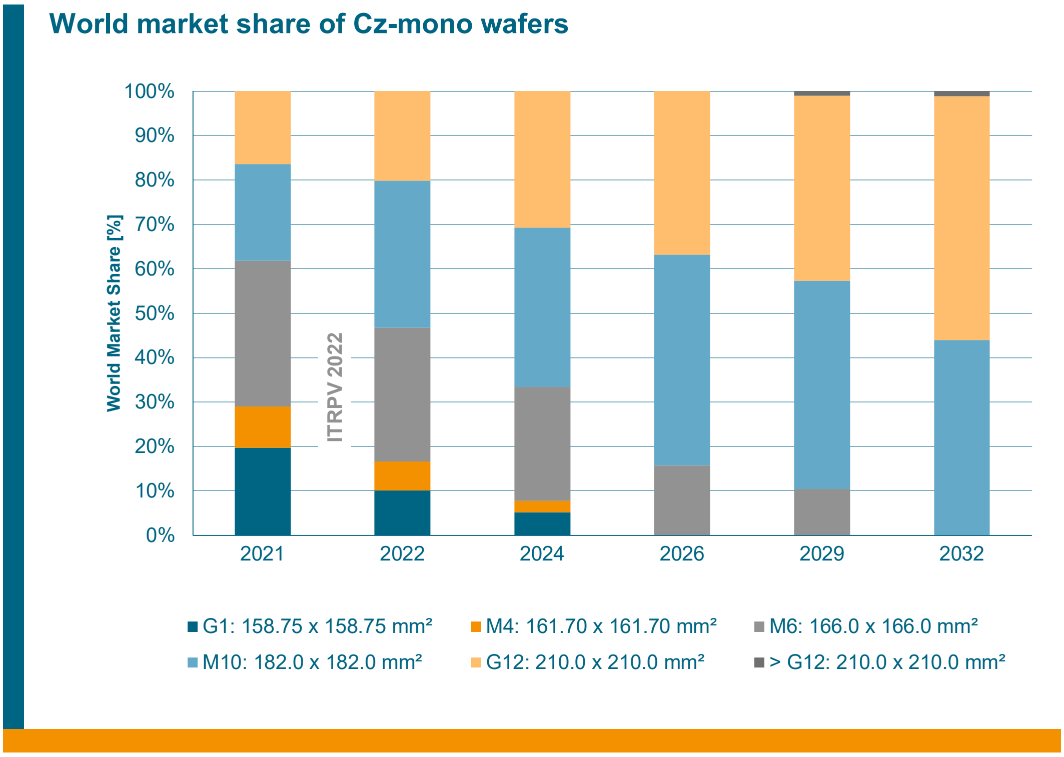


Fig. 10: Expected trend of Cz-mono-Si wafer size in mass production.

A standardization of the different wafer formats is necessary to enable availability of appropriate production machines and materials like glass and foils especially for the manufacturing of modules with new wafer formats. SEMI is currently working to update the Si wafer spec for PV solar cells [22].

6. Result of 2021 | Cell

6.1. Materials

Metallization pastes/inks containing silver (Ag) and aluminum (Al) are the most process-critical and most expensive non-silicon materials used in current c-Si cell technologies. Paste consumption therefore needs to be reduced.

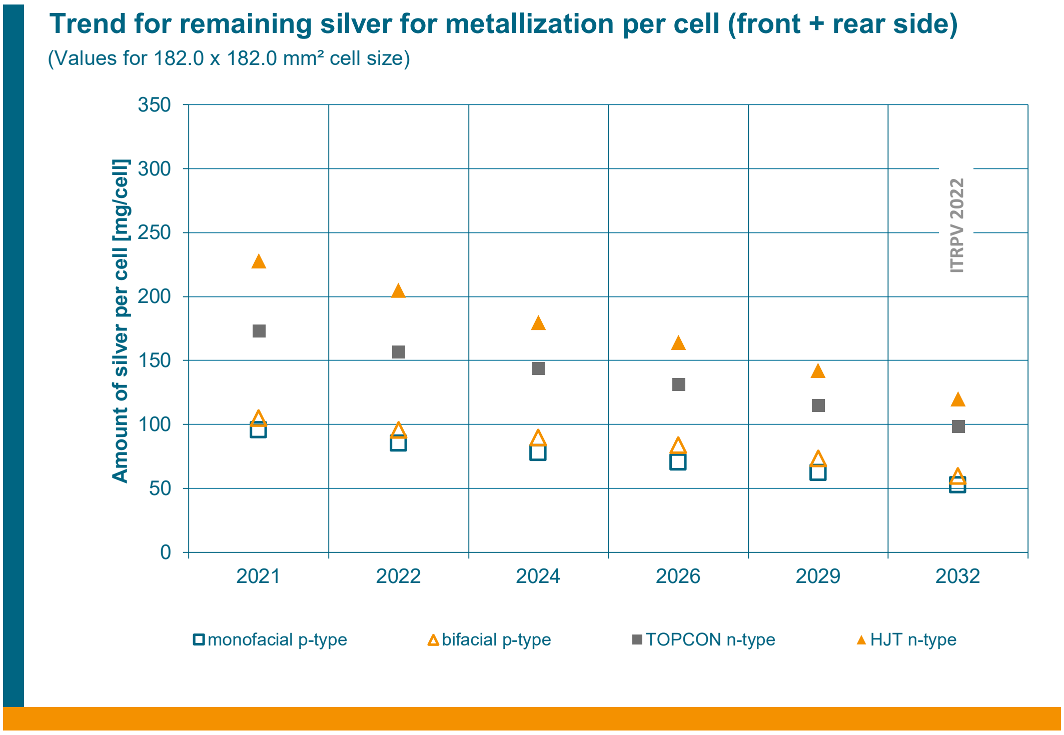


Fig. 11: Trend for remaining silver per cell for different cell concepts in M10 wafer format (182.0 x 182.0 mm²).

Fig. 11 shows our expectation regarding the future reduction of the silver that remains on 182.0 x 182.0 mm² (M10) cells of different p- and n-type cell concepts after processing. The cell area increase compared to former editions of the ITRPV does not influence the trend but only the absolute value.

To get a better understanding of the Ag consumption, Fig. 12 shows the corresponding cell level silver consumption per Wp calculated with the expected cell efficiencies according to Fig. 34. Values in mg/Wp are equal to t/GWp.

The reduction of remaining silver per cell is expected to continue during the next years. The current study found about 13.2 mg/W on cell level as the median value in 2021 and about 12 mg/W mg in 2022 for standard PERC monofacial and bifacial cells as average in M6 and M10 format. This is close to the assumptions in the 11th editions and emphasizes, that silver reduction is continuing. Anyhow, a reduction down to ≈7.5 mg/W or ≈ 60mg per M10 cell is expected to be reached within the next 10 years for PERC. New developments in pastes and screens must enable this reduction, and this points out again the necessity of a close collaboration between suppliers and cell manufacturers to accept this challenge.

The silver price has been since beginning of 2020 around 800 US$/kg, a quite elevated level about 30% to 40% above the average of the five years before 2020 [23]. This resulted in costs of ≈1.1 US$ cents/W for a 23% mono PERC cell. Bifacial p-type concepts consume about 10% more silver. N-type cell concepts show significant higher silver consumption than p-type PERC: 40% and 60% for TopCon and SHJ concepts respectively. This is mainly due to use of silver for front and entire rear side metallization.

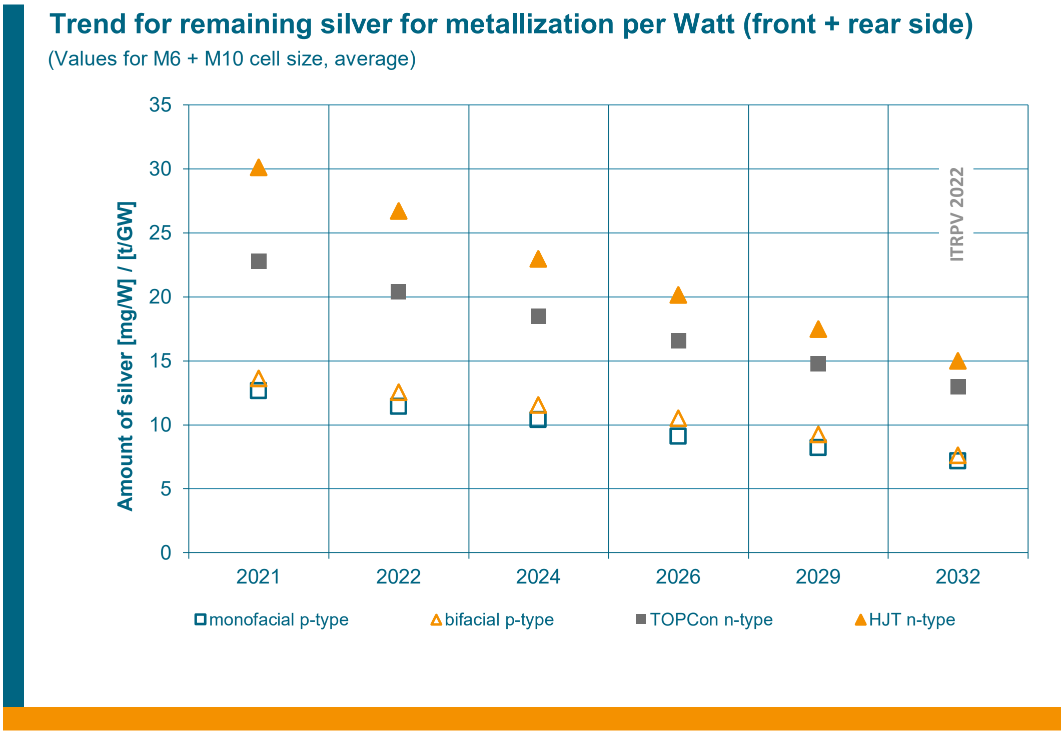


Fig. 12: Trend for remaining silver per cell Wp for different cell concepts as average consumption for M6 and M10 wafer formats and with the cell efficiendcies according to Fig.34 .

Because silver will remain cost critical due to the world market dependency, it is extremely important to continue all efforts to lower silver consumption as a means of achieving further cost reductions. 200 GW PERC cells consume 2640 tons of silver, assuming 13.2 mg/W for 23% PERC average production level. This corresponds to about 8% of world silver supply in 2021 [24]. For TopCon or SHJ technologies this amount would double. So, the continued reduction in silver consumption is essential to meet future production and cost targets for c-Si PV.

On top of a continuous reduction of silver consumption at the cell manufacturing level, silver replacement is still considered. Copper (Cu), as less expensive material, applied with plating technologies, is the envisioned substitute, today in use only for high efficiency back contact cell concepts. It is still assumed that it will be introduced in mass production, but the market share is considered as conservative as in the last editions with about 5% in 2032, no fast breakthrough in copper metallization is expected. Technical issues related to reliability and adhesion must be resolved before alternative metallization techniques can be introduced. Appropriate equipment and processes also need to be made ready for mass production. Silver is expected to remain the most widely used front metallization material for c-Si cells in the years to come.

The trend of remaining aluminum is shown in Fig. 13. We distinguish in this figure between bifacial and monofacial PERC technologies. Bifacial cells need much less rear-side aluminum the rear side grid pattern requires only ≈25% of the corresponding monofacial cell full-side aluminum metallization.

The reduction for the M6 format over the next ten years is assumed to reach down to 620 mg for monofacial and 180 mg for bifacial cell concepts, respectively.

SHJ cells already use lead free pastes. We see lead free pastes to become more used in the mass production of non SHJ c-Si cells.

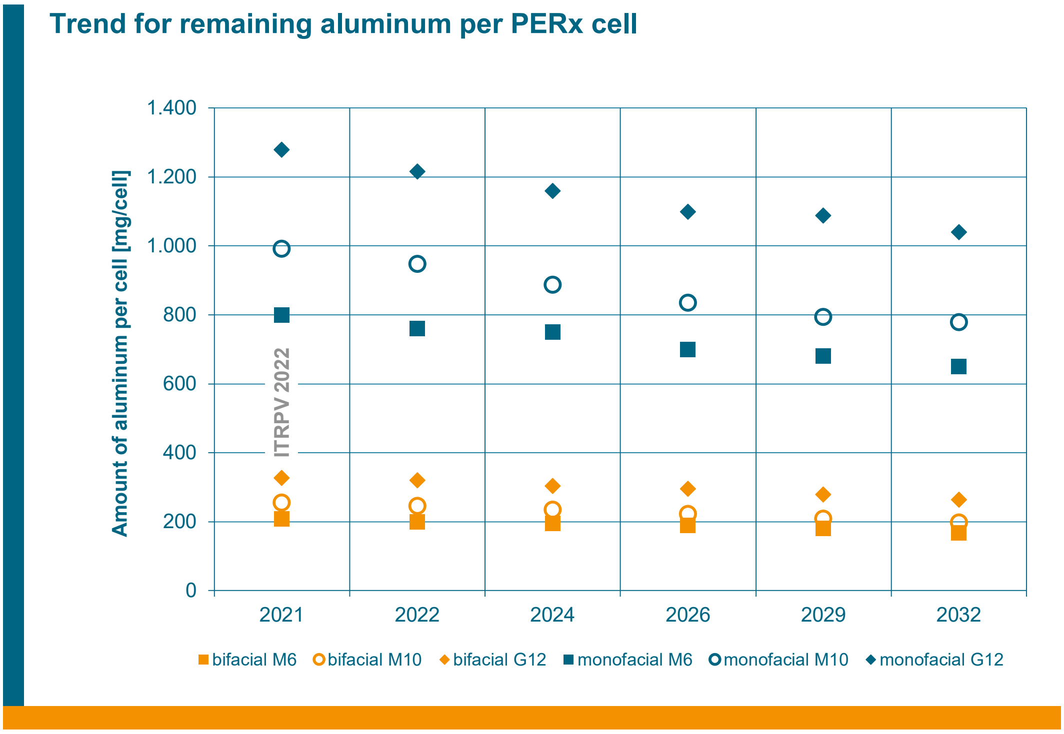


Fig. 13: Trend for remaining aluminum per cell for monofacial and bifacial PERC concepts and for different cell formats.

6.2. Processes

The first production process in cell manufacturing is texturing. Reducing the reflectivity is mandatory to optimize cell efficiency. Mono-Si cell texturing is done with alkaline etching using KOH with additives. This technology is reliable, and throughput optimized with batch processing tools. Only about 1% of mono-Si texturing is assumed to apply Reactive Ion Etching (RIE).

Solar cell recombination losses on the front and rear sides of the cell, as well as recombination losses in the c-Si bulk material, must be reduced in line with high-efficiency cell concepts. The recombination currents J0bulk, J0front, J0rear, indicating the recombination losses in the volume, on the cell's front and rear side respectively, are a reasonable way to describe recombination losses. Fig. 14 and Fig. 15 show the expected recombination current trends for p-type and n-type materials, respectively. The values are in line with the assumptions of former ITRPV editions. Recombination currents can be measured as described in literature [25], or they can be extracted from the I-V-curve if the other J0 components are known. As shown in Fig. 14 the improvement of the silicon material quality for both, mono-Si and mc-Si will continue. This should result in a reduction of the J0bulk value to 70 fA/cm² for p-type mc-Si-like the trend in the 12th edition, mainly due to the shrinking market importance less progress is expected here, J0bulk for mono-Si is expected to reach about 20 fA/cm² within the next 10 years. Reductions of J0bulk will result from further improvements of the crystallization process. J0front and J0rear are expected to improve similar in p-type mono-Si to below 30 fA/cm² in 2032.

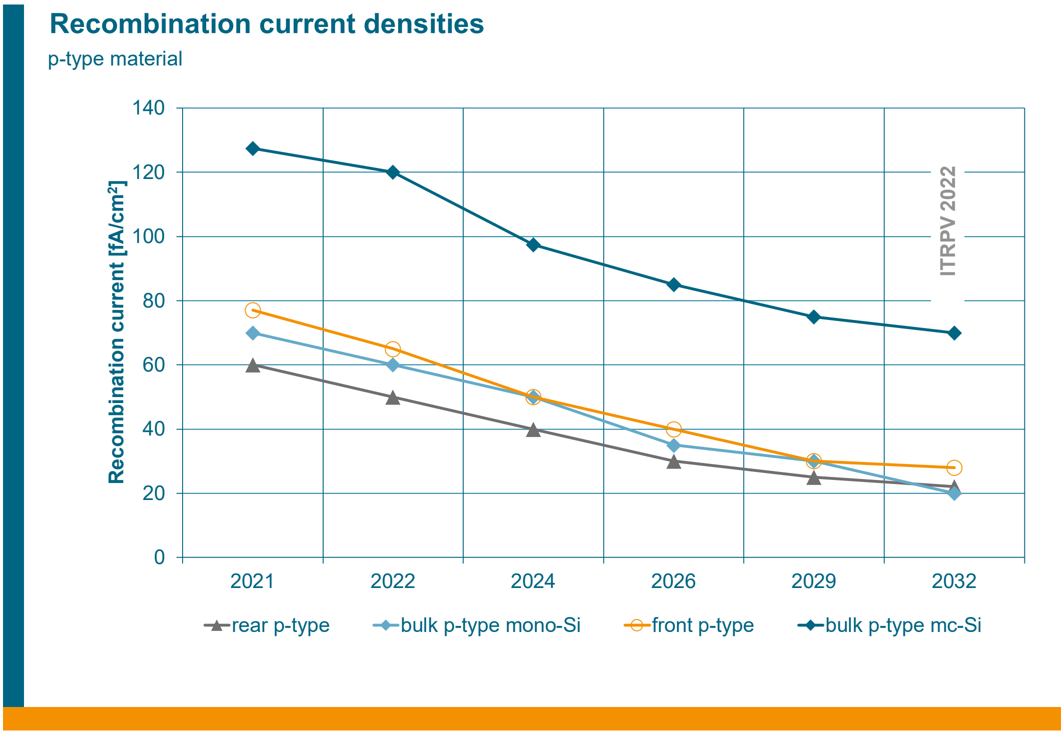


Fig. 14: Predicted trend for recombination currents J0bulk, J0front, J0rear for p-type cell concepts.

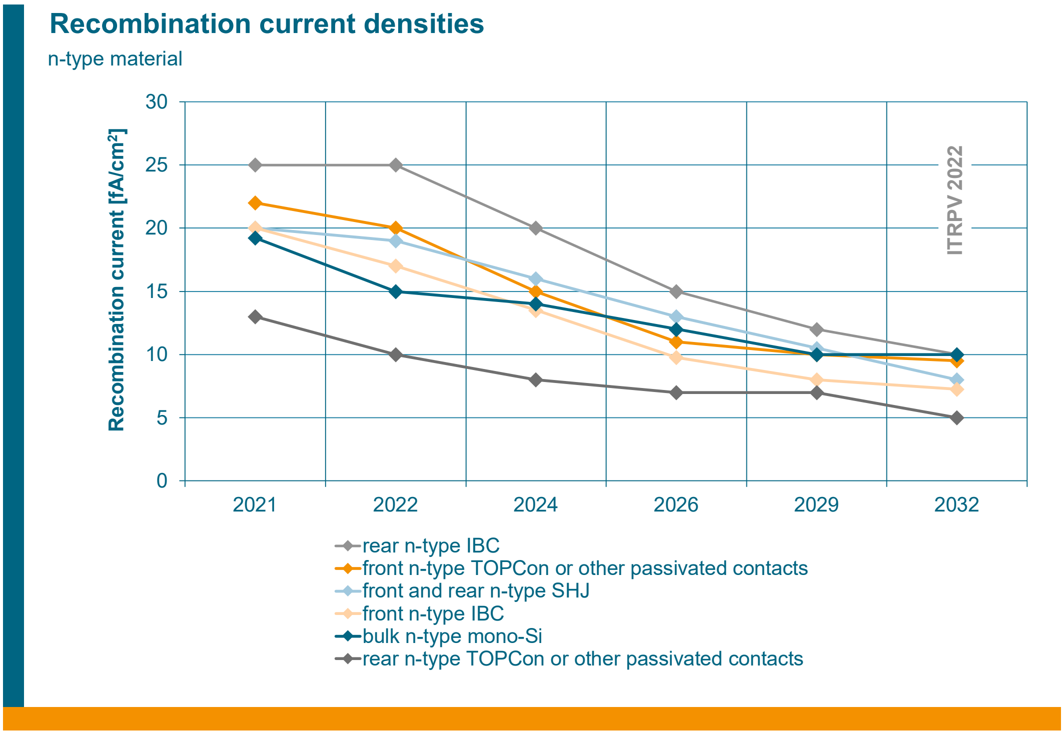


Fig. 15: Predicted trend for recombination currents J0bulk, J0front, J0rear for n-type cell concepts.

Fig. 15 shows that today's n-type mono-Si wafers have J0bulk values below 20 fA/cm², about 30% of the corresponding p-type J0bulk value. J0front and J0rear are also lower for n-type concepts emphasizing the potential for higher cell efficiencies. It is expected that all values will be further reduced to about 10 fA/cm² within the next 10 years. J0rear improvements are linked closely to cell concepts with passivated rear side.

J0front improvements cover all relevant front side parameters (emitter, surface, contacts). A parameter that influences recombination losses on the front surface for cell concepts with diffused pn junctions is the so-called emitter sheet resistance. A high sheet resistance is beneficial for low J0front. Sheet resistances well above 100 Ohm/square can be realized with and without selective emitters. If a selective emitter is used, sheet resistance values refer only to the lower doped region.

Phosphorus is used as dopant to form the pn junction in p-type cell concepts. Fig. 16 shows the current situation for homogenous and selective Phosphorus doping: today's sheet resistance of homogenous doped p-type emitters is > 110 Ohm/square and it is expected to increase to 150 Ohm / square. Selective doping allows higher sheet resistances: 150 Ohm/square are standard in 2022. An increase beyond 190 Ohm/square is expected within the next years.

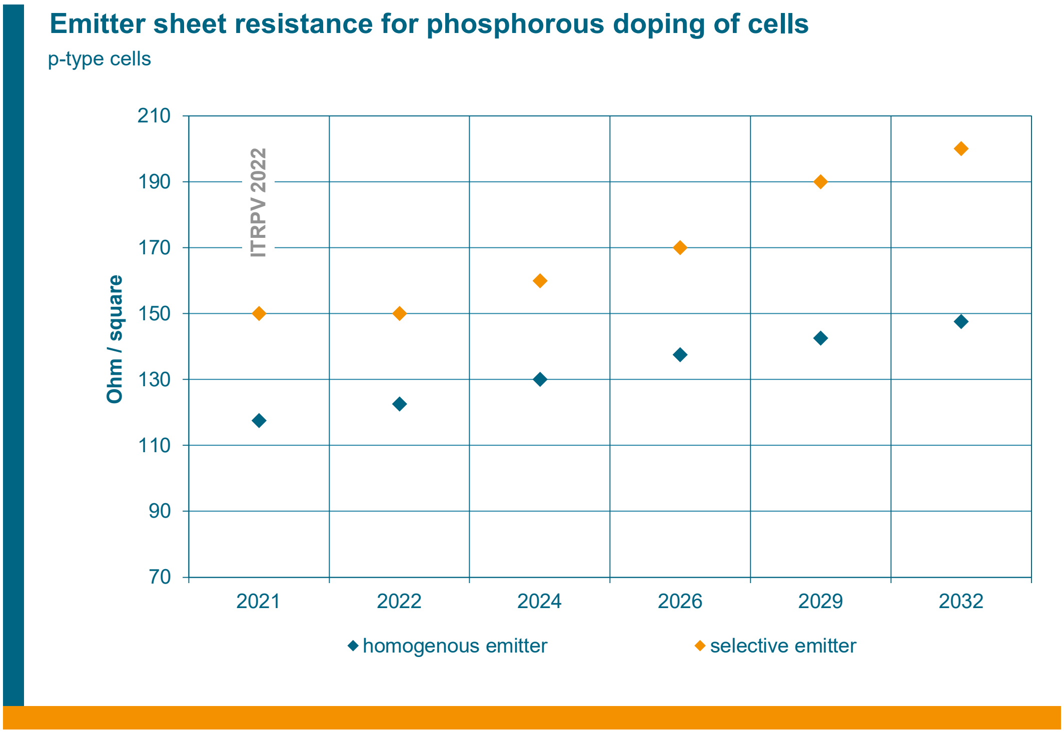


Fig. 16: Expected trend for emitter sheet resistance of Phosporous doped emitters for p-type cell concepts. In case of selective emitter the sheet resistance value refers only to the lower doped region.

Fig. 17 shows the expected market share of different technologies for phosphorous doping in p-type cell processing. Homogeneous gas phase diffusion is a mature, cost-efficient doping technology but high sheet resistances are challenging to contact for highest cell efficiencies. Selective emitter processes resolved this limitation. Applied after standard POCl3 gas phase diffusion, selective emitter processes enable the contacting of lowest phosphorous concentrations with standard metallization pastes. Therefore, selective emitter diffusion techniques became mainstream in 2021 with a market share of 60% and will dominate the future. Laser doped selective emitters are the technology of choice.

Boron doping for n-type cells is mainly using the BBr_3 thermal diffusion technique as shown in Fig. 18. This is in line with the findings of former ITRPV editions. BCl_3 doping is seen to become interesting in the next years with up to 40% market share. Ion implantation is supposed to stay at low share of < 1%. Alternative processes are not seen with significant market shares so far.

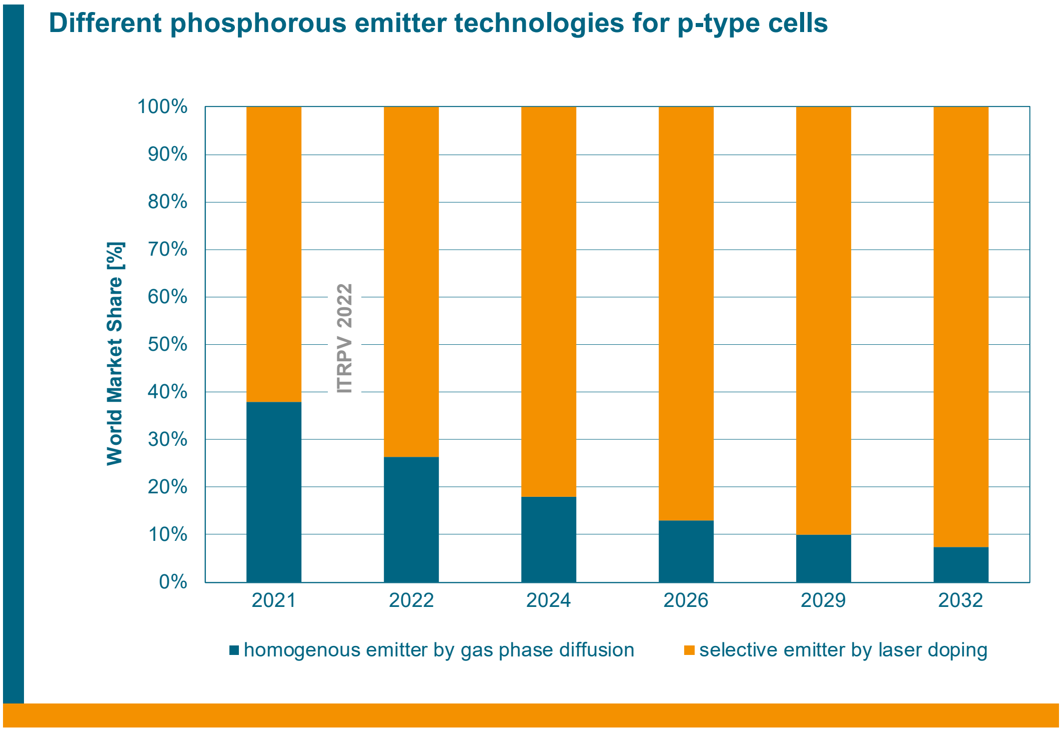


Fig. 17: Expected market share for different phosphorous emitter diffusion technologies for p-type cells.

Boron is the dopant to form the pn junction in n-type concepts. The predicted trend for n-type emitters is shown in Fig. 19. An emitter sheet resistance of over 100 Ohm/square is mostly used in 2022's boron diffused emitters. An increase to above 130 Ohm/square is expected within the next 10 years.

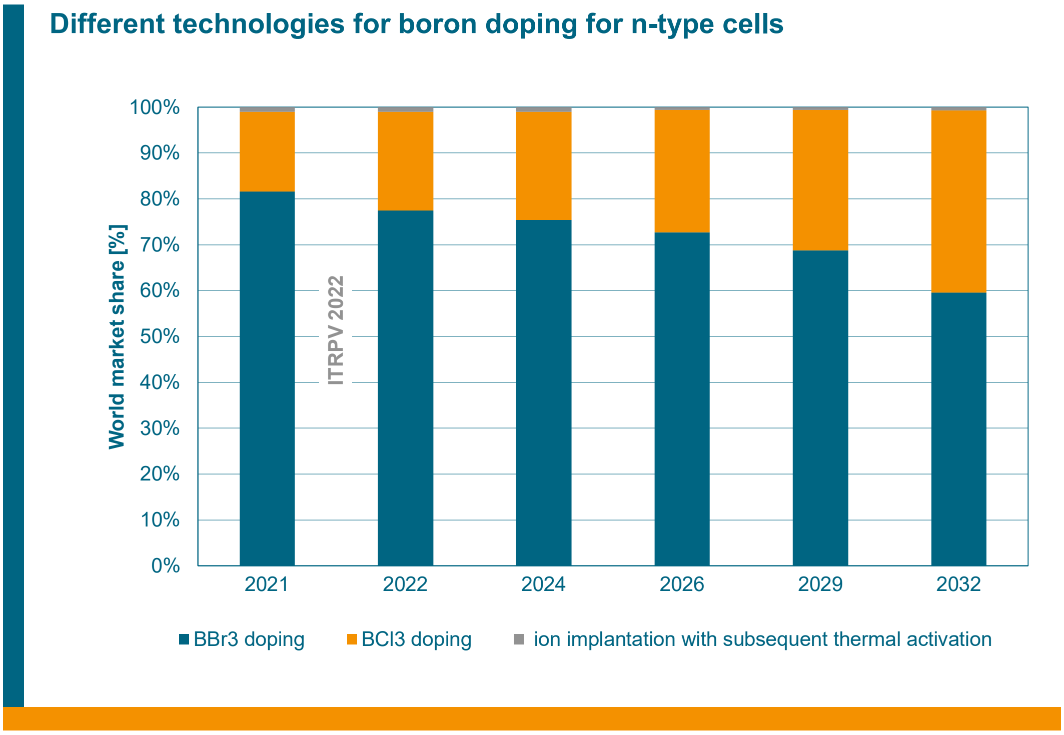


Fig. 18: Expected market share for different technologies for boron doping for n-type cells.

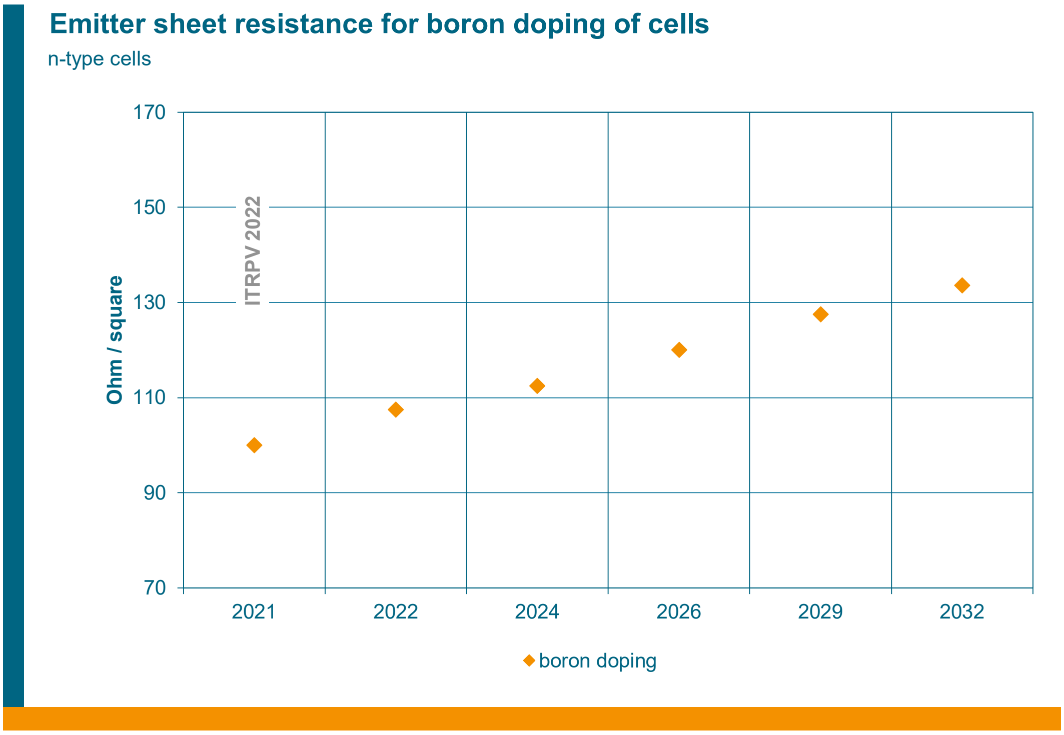
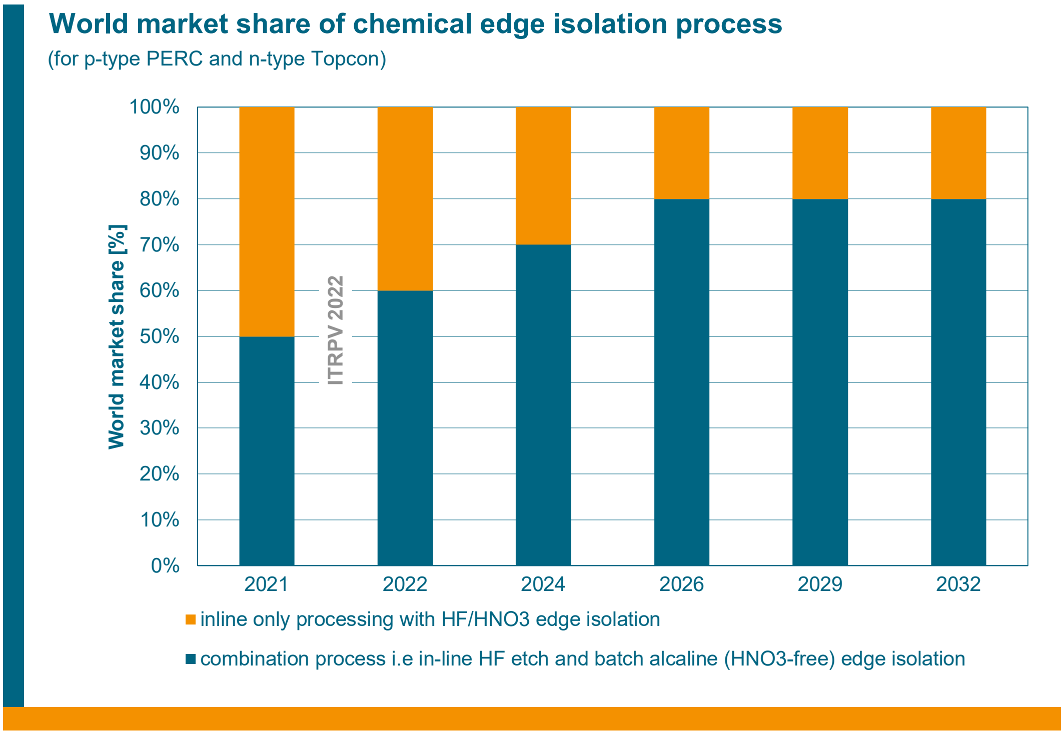


Fig. 19: Expected trend for emitter sheet resistance for boron doping for n-type cell concepts.

To separate the pn junction from bulk, an edge isolation is required. Wet chemical edge isolation is doing this job in today's manufacturing lines. Fig. 20 shows the market share of the edge isolation process types. In-line processing with HF/HNO_3 has been until 2021 the mainstream technology. We see that HNO_3 free processing is gaining market share despite the required combination of in-line HF oxide etching and batch KOH (alkaline) silicon removal. Benefits are the substitution of expensive HNO_3 and a less expensive process exhaust gas treatment due to the elimination of nitrous fumes.



Fig, 20: Market trend of chemical edge isolation process used for isolation of pn junctions in corresponding cell technologies.

Beside the edge isolation process also rear side treatment is required. Fig. 21 shows that in-line KOH polishing will fast become the dominating technology.

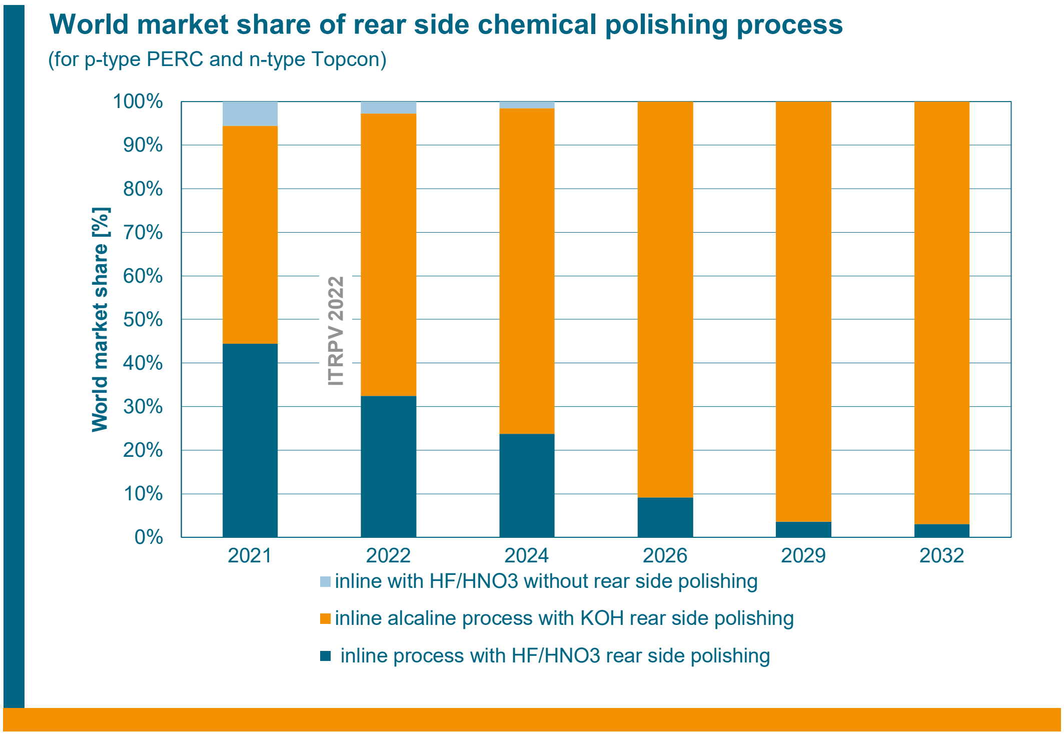


Fig. 21: Expected market trend for required rear side polishing processes.

Since 2013, cell concepts using rear side passivation with dielectric layer stacks have been in mass production (PERC/PERT/PERL technology) and are mainstream today in c-Si PV as discussed in 6.3. PERC on p-type has been using Aluminum oxide (AlO_x) as rear side passivation layer since the beginning. Fig. 22 shows the expected market shares of different technologies for the deposition of AlO_x passivation layers on p-doped silicon interfaces, suitable for n-type and p-type cell concepts with diffused pn junctions. The market share of remote plasma PECVD Al_2O_3 in combination with a capping layer will continuously shrink within the next 10 years to about 15%. This former mainstream technology for PERC cell concepts is about to be phased out. New built cell production capacities will use direct plasma PECVD Al_2O_3 with integrated capping layer deposition or ALD Al_2O_3 deposition techniques in combination with separate capping layer deposition.

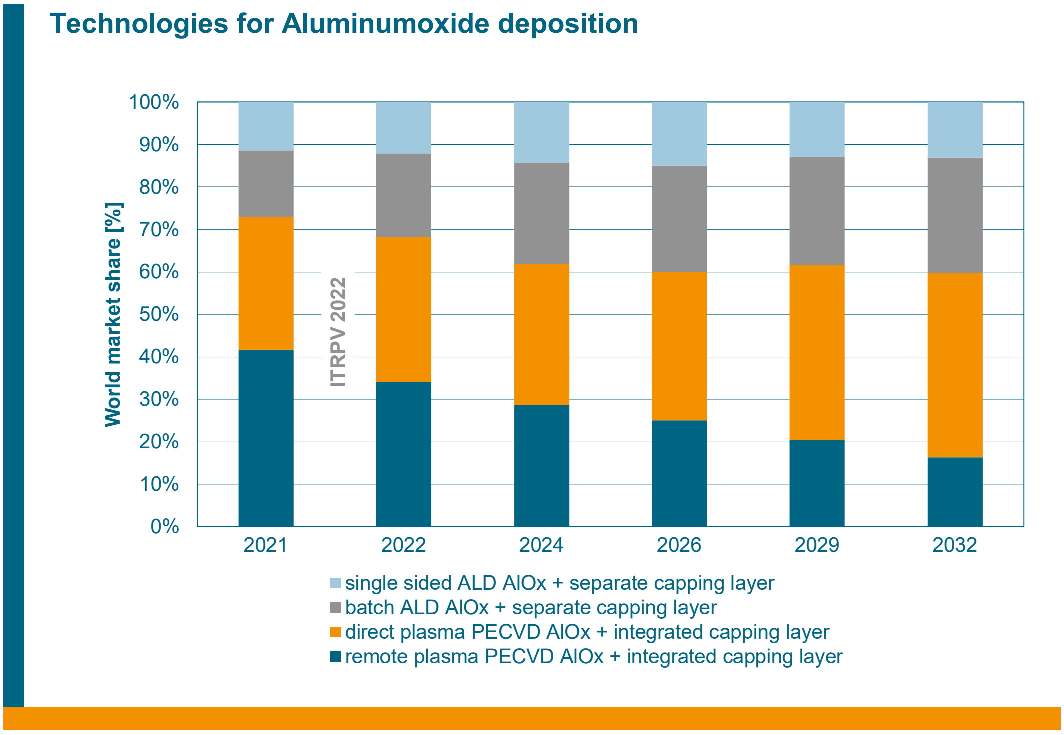


Fig. 22: Predicted market share of technologies for AlOx-based passivation layers.

Forming electrical contact via tunneling of electrons instead of forming ohmic contacts to the bulk silicon is used for rear side contacting in TOPCon (Tunnel Oxide Passivated Contacts) cell concepts. This technique further reduces the forming of recombination centers at the interface and eliminates recombination current losses at resistive bulk contact.

Tunnel oxide formation can be done in an individual process step or in in situ with another process. In situ formation in combination with another process is expected to become the preferred technique.

The forming of the poly-Si layer can be done by LPCVD, by PECVD, or by PVD. Fig. 23 indicates that LPCVD is currently dominating but PECVD is expected to become the preferred technology within the next years.

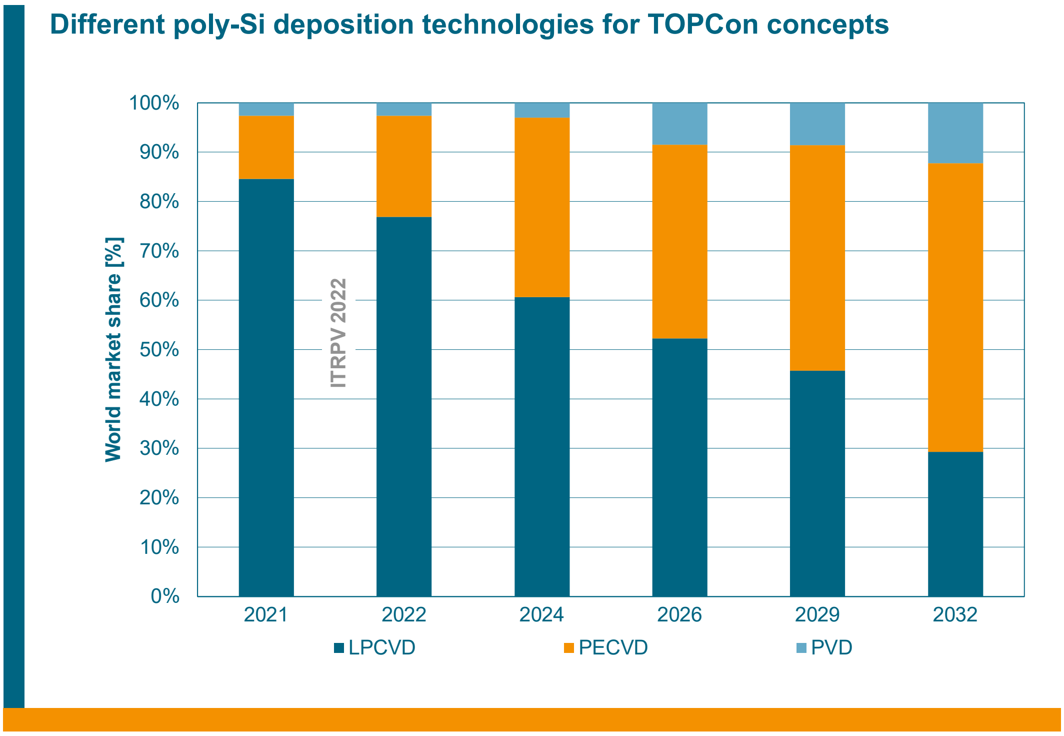


Fig. 23: Expected trend of forming the polysilicon layer of TOPCon contacts.

Fig. 24 shows the expected share of doping methods for the poly-Si layers. In situ doping is expected to become the future mainstream. This is quite in line with the trend in Fig. 23: doping of poly-Si is done mainly depending on the deposition technology. While ex situ doping is preferred for LPCVD and PVD, in situ doping is used in PECVD layer doping.

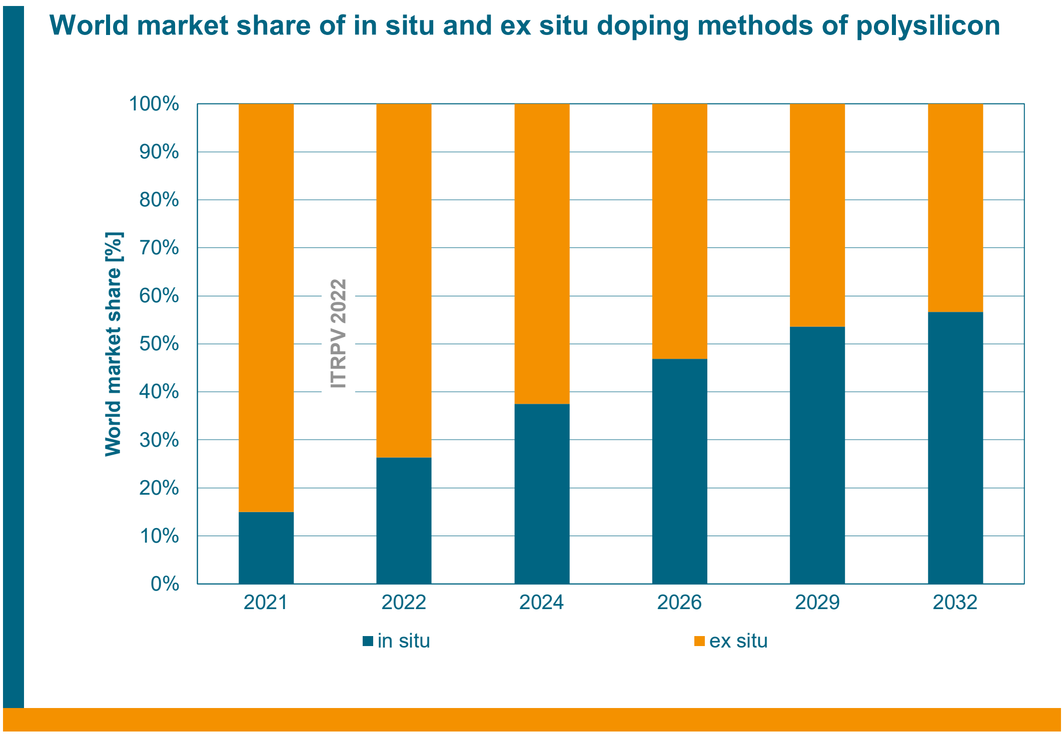


Fig.24: Expected trend for forming the tunnel oxide and doping the ploy Si capping layer in passivated contact forming.

Fig. 25 shows the anticipated thickness trend of the poly-Si layer deposited for TOPCon concepts. Contacting the emitter and the rear side of the solar cell is the final processing sequence in solar cell manufacturing and a key process regarding cost, efficiency, and quality.

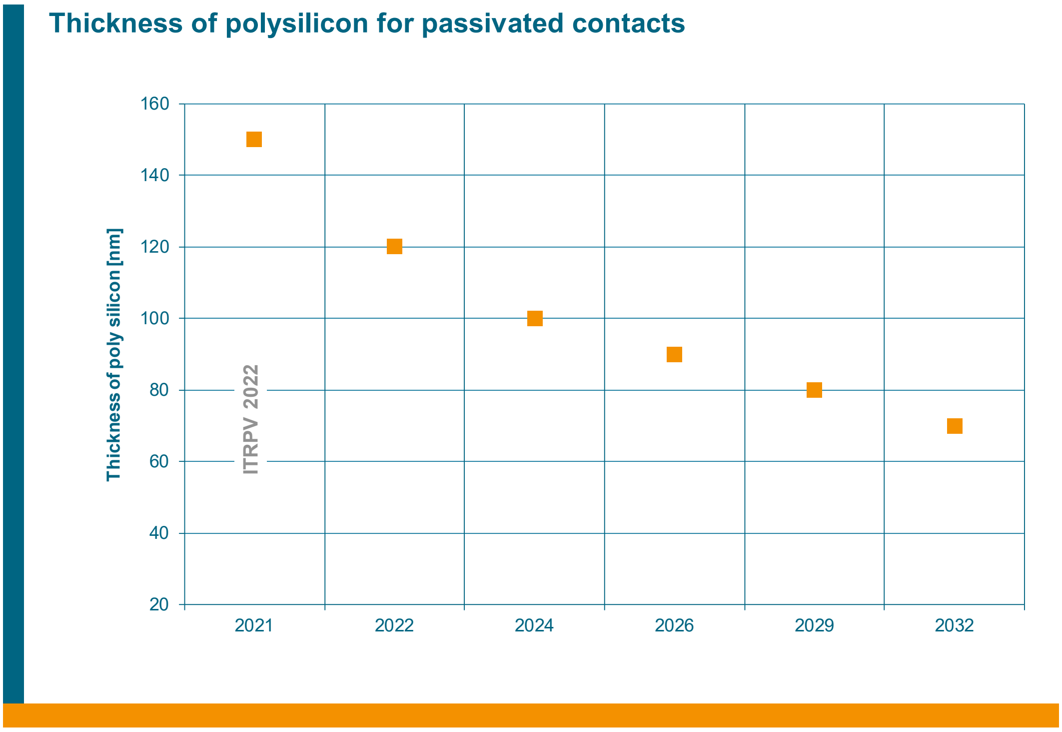


Fig. 25: Expected trend of polysilicon thickness for TOPCon layer stack formation.

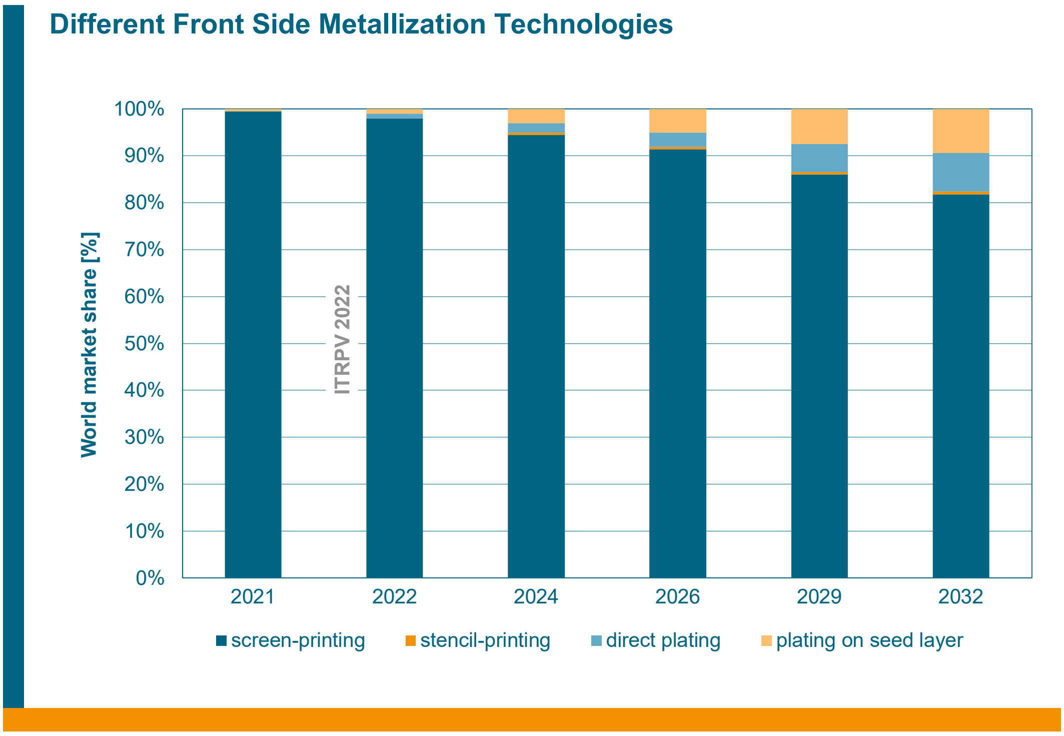


Fig. 26: Expected market share of front side metallization technologies.

Screen printing has been the technology of choice for front and rear side metallization since the beginning of c-Si solar cell mass production. We see screen printing also in the future as the mainstream metallization technology as shown in Fig. 26. Plating is still considered to be introduced as front side metallization technology with market shares above 5% after 2026 onwards. Other technologies like aerosol, inkjet or dispensing techniques are no more present in the mass manufacturing market.

Three different approaches for high quality front side print exist. Fig. 27 summarizes the available technologies and their estimated market share during the next 10 years. New front side metallization pastes enable the contacting of the previously discussed low doped emitters without any significant reduction in printing process quality. Single print technology will stay mainstream until 2022. Dual printing will take over the lead in future as new capacity will be equipped from the beginning for this approach. Double printing has a constant small market share of ≈10%. Dual und double print require an additional printing step with fine-alignment capabilities.

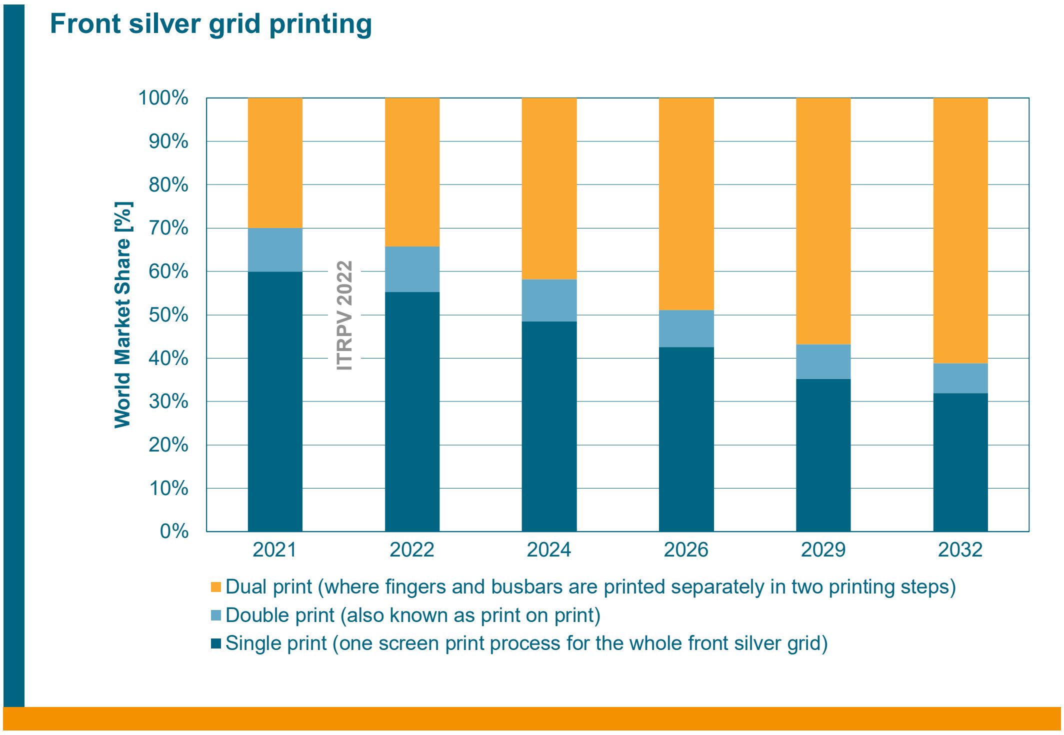


Fig. 27: Expected market share of different front side printing techniques.

A reduction in finger width is one method yielding in efficiency gain and cost reduction, but only if it is realized without significantly increasing finger resistance. Furthermore, contact with a shallow emitter needs to be established reliably. One possible way to achieve these goals is to use a selective emitter technology as shown in Fig. 16, preferably without significantly increasing processing costs.

Reducing finger width reduces shadowing, but to maintain conductivity a trade-off has to be made, if the roadmap for silver reduction, as discussed in chapter 6.1. will be executed. Finger widths of about 30 µm are standard in 2022 as shown in Fig. 28. A further reduction to below 20 µm appears possible over the next 10 years.

Beside the reduction of finger with the printing alignment accuracy requirements are of increasing importance.

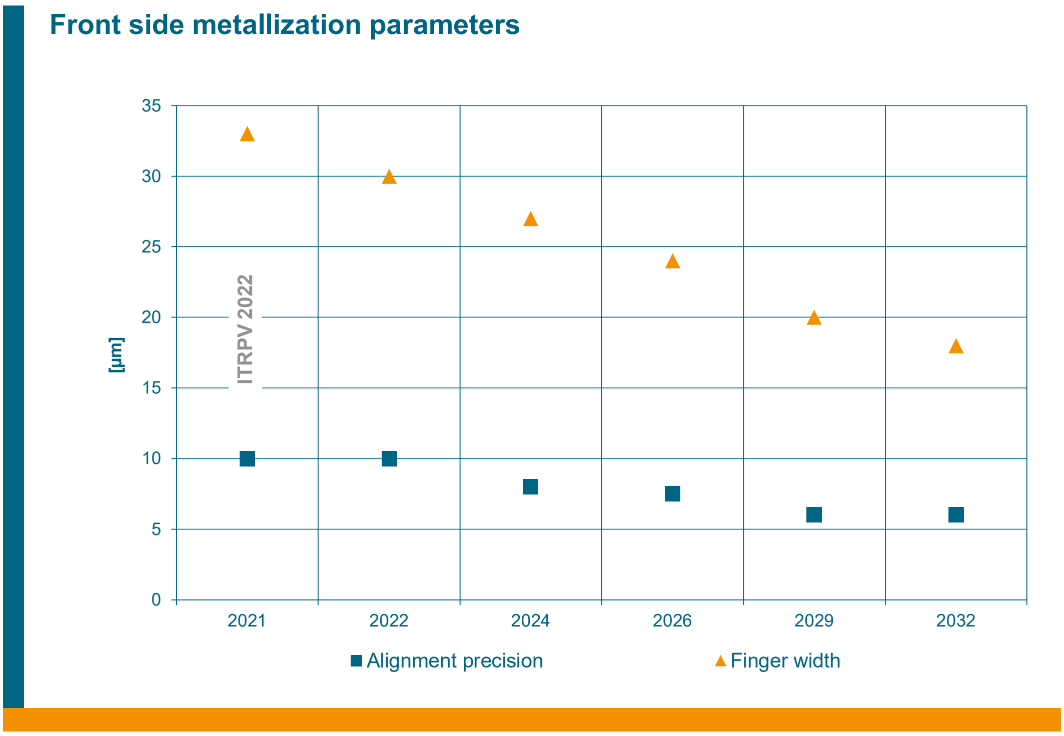


Fig. 28: Predicted trend for finger width and alignment precision in screen-printing. Finger width needs to be reduced without any significant reduction in conductivity.

Dual print separates the fingerprint from the busbar (BB) print, enabling the use of special busbar pastes with less silver but excellent soldering capabilities. Busbar less cell interconnect techniques can even omit the busbars completely. For reliable module interconnection, and for bifacial cells, a good alignment accuracy is important in metallization - an alignment accuracy of better than 10 µm (@+/- 3 sigma) will be required in the future as Fig. 28 shows. This will be necessary especially regarding an improved alignment to subjacent structures as in the case of selective emitter structures.

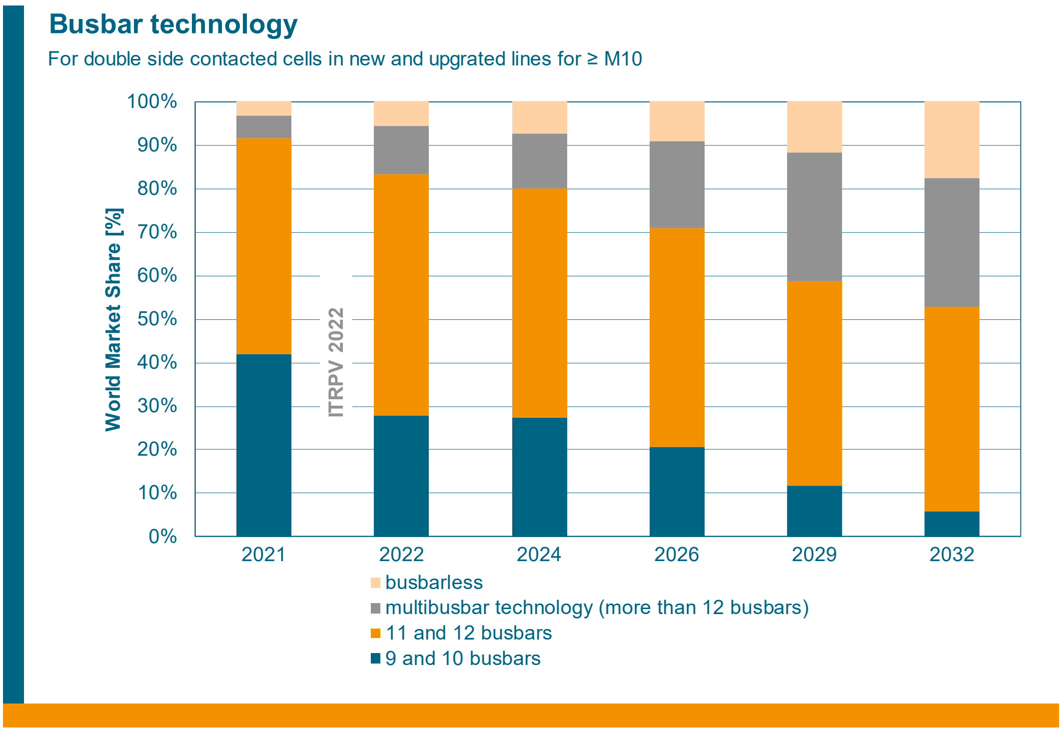


Fig. 29: Market share for different busbar technologies.

Reducing the finger width is going in parallel with increasing the number of busbars. Fig. 29 shows details on this metallization trend for cells with the format ≥ M10. Layouts with 5 and 6 BBs are not used for large wafer formats and are expected to be phased out within the next 5 years, also for cells ≤ M6. Layouts with 9 to 12 BBs are dominating the market. Layouts with >12 BB and BB-less layouts are expected to gain market share. BB-less technologies support minimum finger widths shown in the Fig. 28 trend. Nevertheless, BB-less layouts will require new interconnection technologies in module manufacturing that - in best case - should be implemented by upgrading of existing stringing tools.

Optimizing productivity is essential to be cost competitive. Increasing the throughput of the equipment in order to achieve maximum output is therefore a suitable way to reduce tool related costs per cell and hence per Wp. To optimize the throughput in a cell production line, both, front-end (chemical and thermal processes) and back-end (metallization and classification) processes should have equal capacity. In former editions of the ITRPV we considered two scenarios: an evolutional optimization approach to optimize existing tool sets and a progressive scenario, for trends of new equipment's, with higher process throughputs. As discussed in chapter 5.3., we currently see that larger wafer formats ≥ M10 will become mainstream. New tools will be capable to process all those formats as well as M6. In the 13th edition we show throughput trends for new tools suitable for M10: the medium scenario.

In Fig. 30 a, b, and c we summarize the expected throughput trends of new tools capable for processing cell formats ≥ M10 more detailed than in former editions.

Fig. 30 a shows the expected throughput trend in chemical processing and pure thermal processing: diffusion, oxidation, and annealing, Chemical processing tools are leading the throughput list with about 10,000 wafers/h for 2022 in batch processing e. g. for texturing. Boron diffusion requires long process times and therefore the throughput is limited to about 3,800 wafers/h in 2022. Throughput is expected to increase to 6,000 wafers/h within the next 10 years.

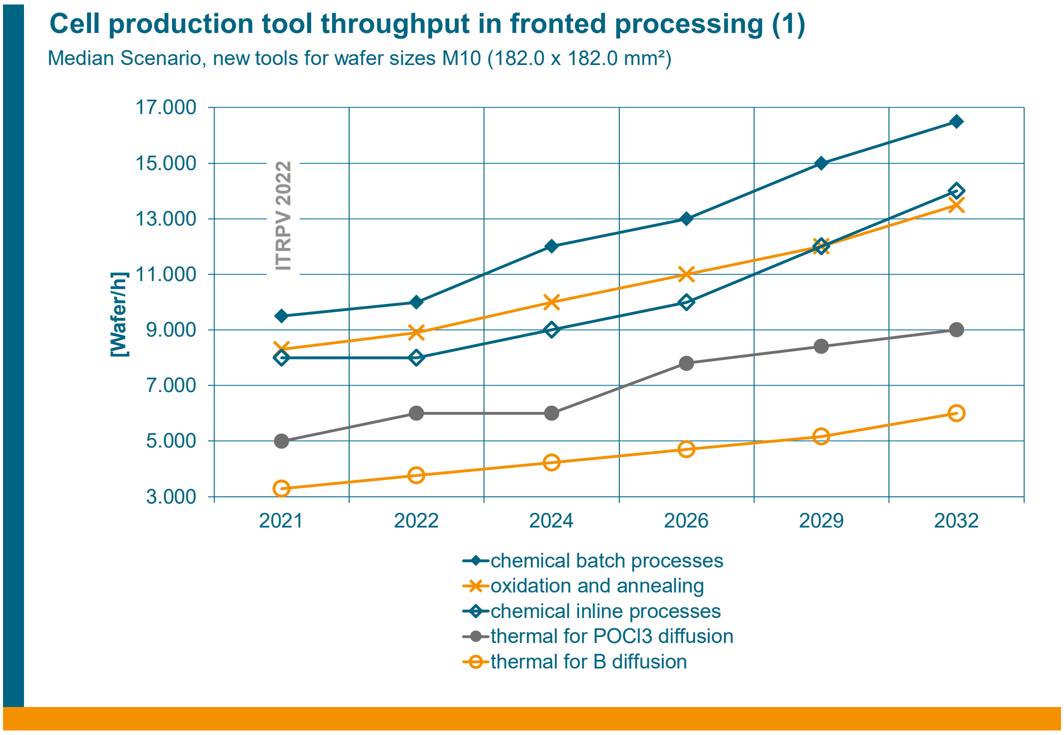


Fig. 30 a: Predicted trend for throughput per tool of cell production tools in the frontend.

Fig. 30 b shows the expected throughput trends for layer deposition tools. ALD is leading in this process field with 10,000 wafers/h in 2022 and expected 12,000 wafers/h from 2024 onwards.

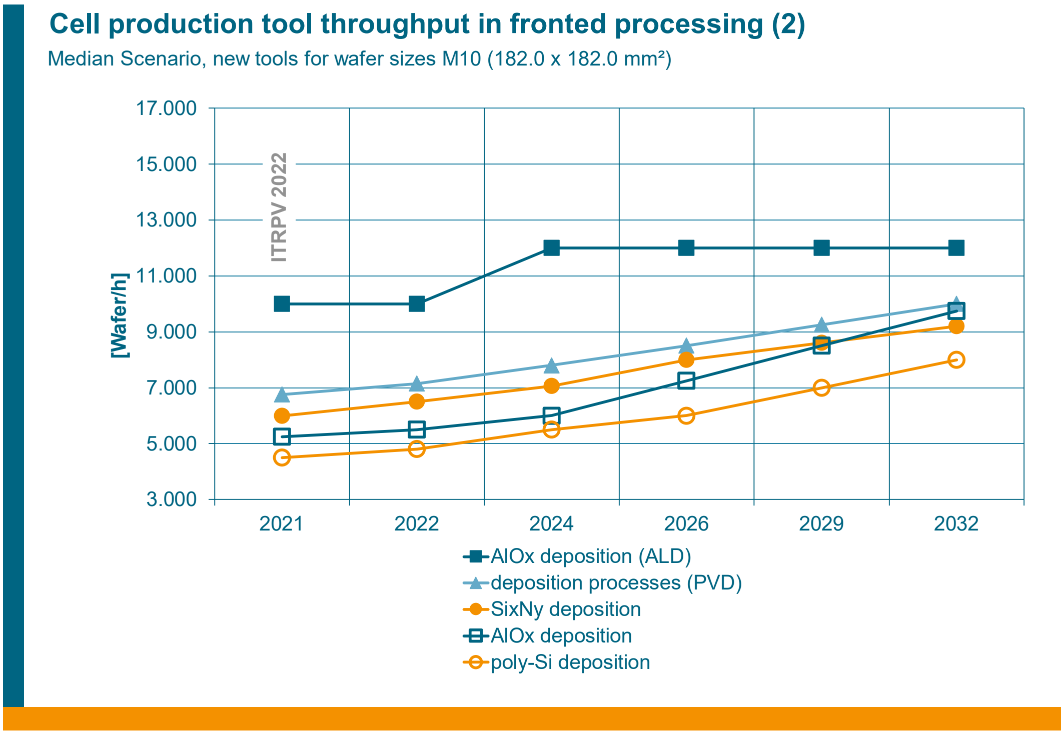


Fig. 30 b: Predicted trend for throughput per tool of cell production tools for layer deposition.

Fig. 30 c shows the throughput trend in cell processing backend. Screen printing tools with throughputs of ≈7,200 M10 wafers/h are available on the market today. Laser contact opening before printing, as well as firing and testing after screen printing are installed in line in contemporary cell production lines, meeting the same throughput figures. Further improvements in this field will depend strongly on the progress made with the screen-printing technology that currently focuses on smaller line width and lower paste consumption.

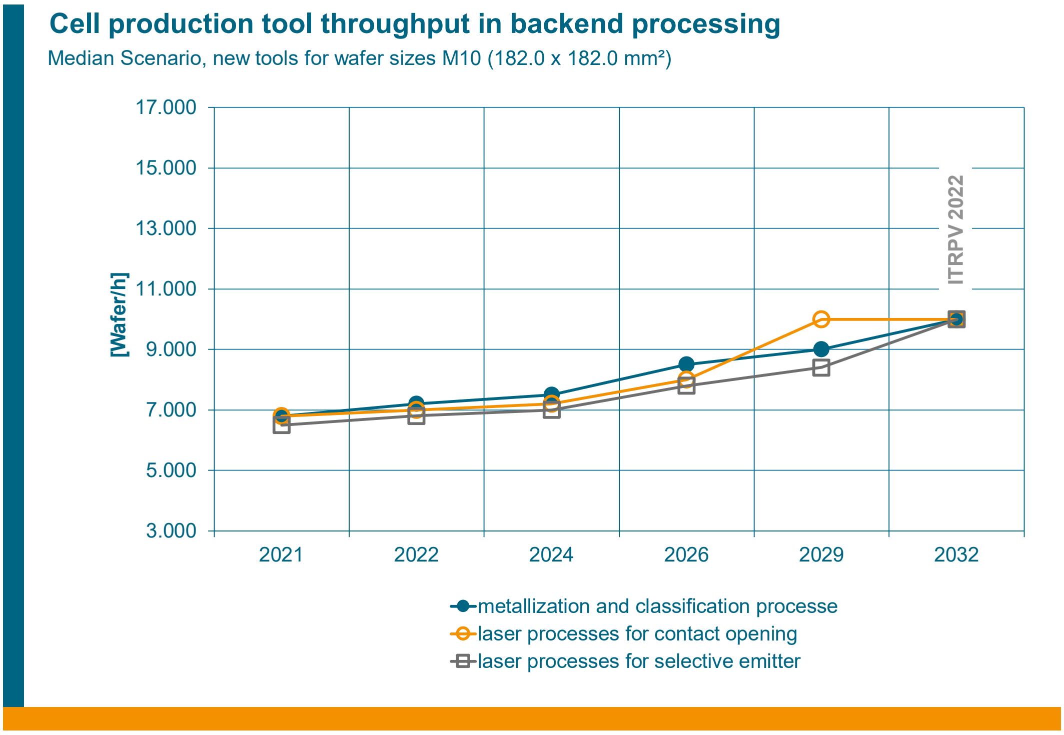


Fig. 30 c: Predicted trend for throughput per tool of cell production tools in backend processing.

6.3. Products

The BSF cell concept is about to be phased out within 2022. Nevertheless, the matured concept of diffused and passivated pn junctions will be further used in the mainstream with different other rear side passivation technologies (PERC/PERL/PERT/TOPCON).

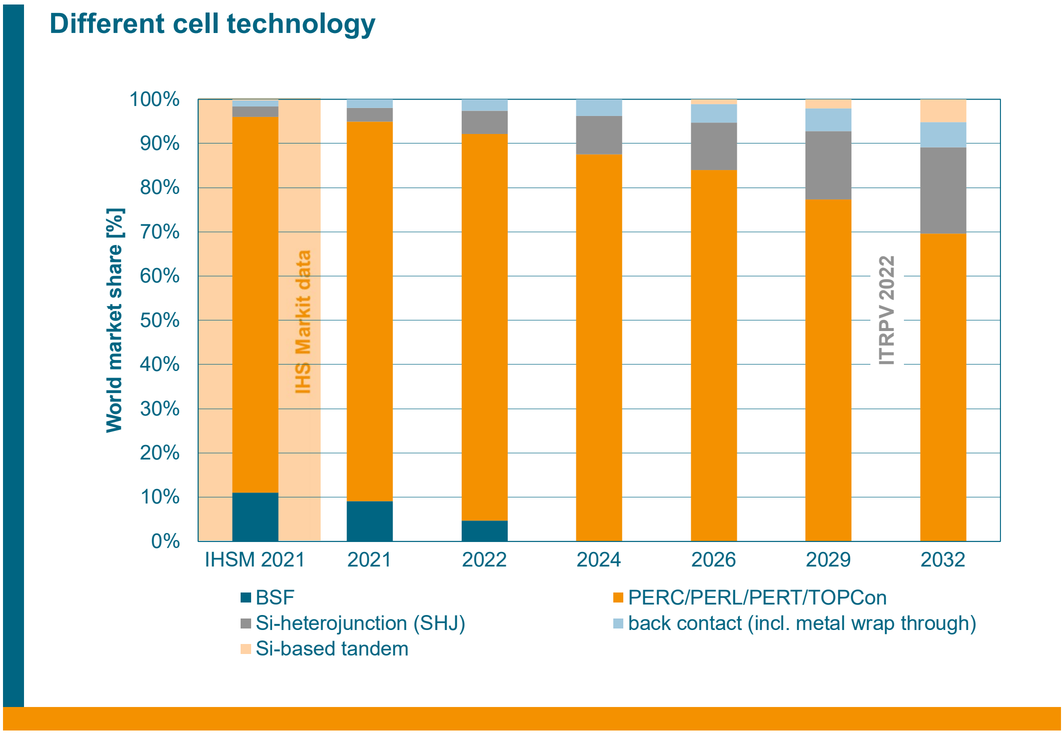


Fig. 31: Market shares for different cell technologies. IHS Markit data for 2021 are indicated as reference [19].

2021 market share of PERC/PERL/PERT/TOPCON was found to be ≈85% as shown in Fig. 31. This is in line with IHS Markit assumptions [19]. PERC/PERT/PERL/TOPCON will dominate the market over the next years. SHJ cells are expected to gain a market share of about 10% after 2024 and close to 20% by 2032.

Fig. 31 also confirms again the market dominance of double-sided contact cell concepts. Rear-side contact cells are not expected to have significant market share: we assume a change from ≈2% in 2021 to nearly 5% in 10 years. Si-based tandem cells are expected to appear after 2024 in mass production a delay compared to the assumptions in the 12th edition.

Fig. 32 highlights trends in cell technologies with passivated, diffused pn junction on the front side and passivated rear side. There are different approaches to realize such cells. The most mature approach uses p-type material with a passivating layer of Al_2O_3 and a SiN_x capping layer as discussed in chapter 6.2. In 2021 about 10% of PERC cells were produced in this technology with p-type mc-Si material, 85% were PERC on p-type mono-Si. This share is expected to stay on a quite similar level in 2022. But it is expected that the PERC on p-type mono-Si share will decrease to about 40% within the next 10 years. PERC on mc-Si material will also be phased out until 2025. Concepts on n- and p-type material with passivated contacts, using tunnel oxide passivation stacks at the rear side, will gain market share from about 10% in 2022 up to 58% within the next 10 years. We estimate that n-type bulk material will become mainstream for concepts with passivated contacts and that only a much smaller share will deploy p-type material.

All cell types discussed in Fig. 31 as well as SHJ cells can capture the light from the front and from the rear side if the electrical contacts are designed accordingly. This cell types can therefore be perfectly used for bifacial light capturing. Fig. 33 shows the expected market trend for bifacial cells. The market share of 50% in 2021 is expected to increase significantly to 85% within the next 10 years. Bifacial cells can be used in modules with transparent rear side (bifacial modules) or in conventional, monofacial modules.

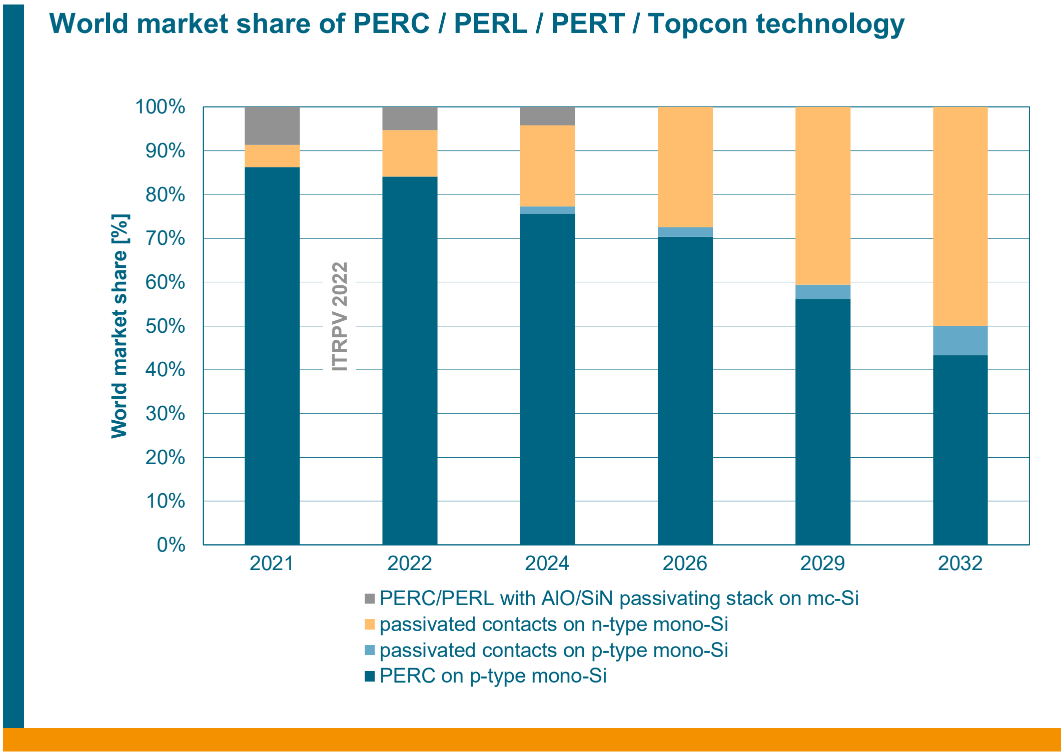


Fig. 32: Market share for c-Si cell concepts with pn-junction on the front and different rear side passivation technologies.

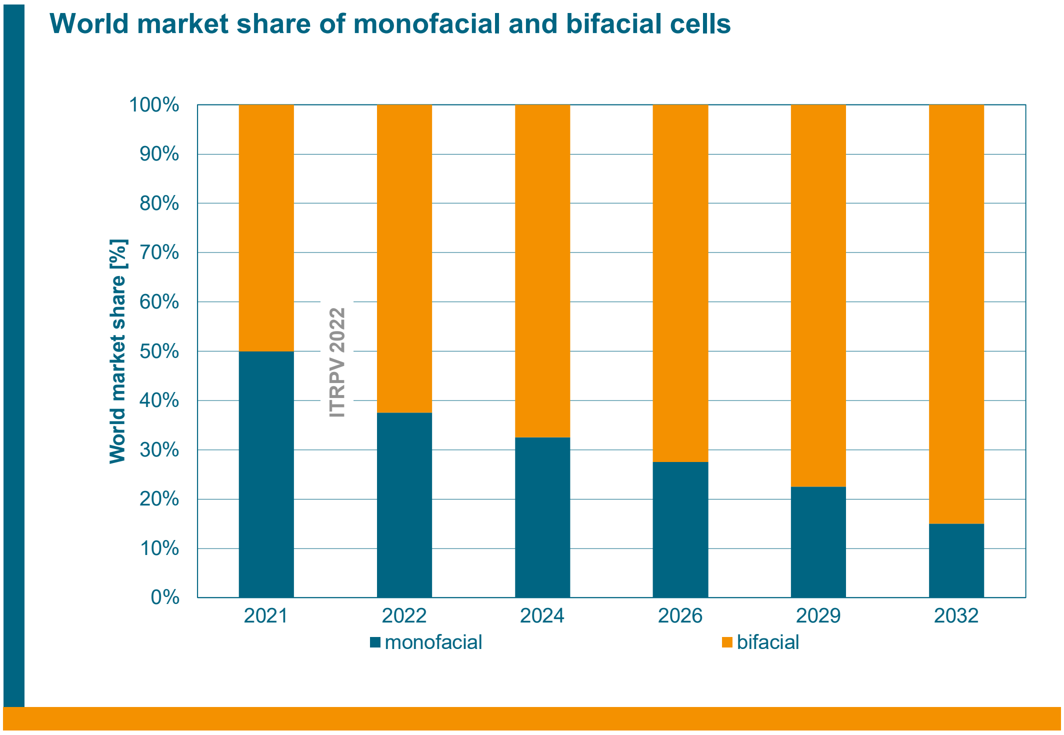


Fig. 33: Market share for bifacial cell technology.

Fig. 34 illustrates the expected average stabilized front-side cell efficiencies of state-of-the-art mass production lines for double-sided contact and rear-contact cells on different wafer materials. The plot shows that there is potential for all technologies to improve their performance.

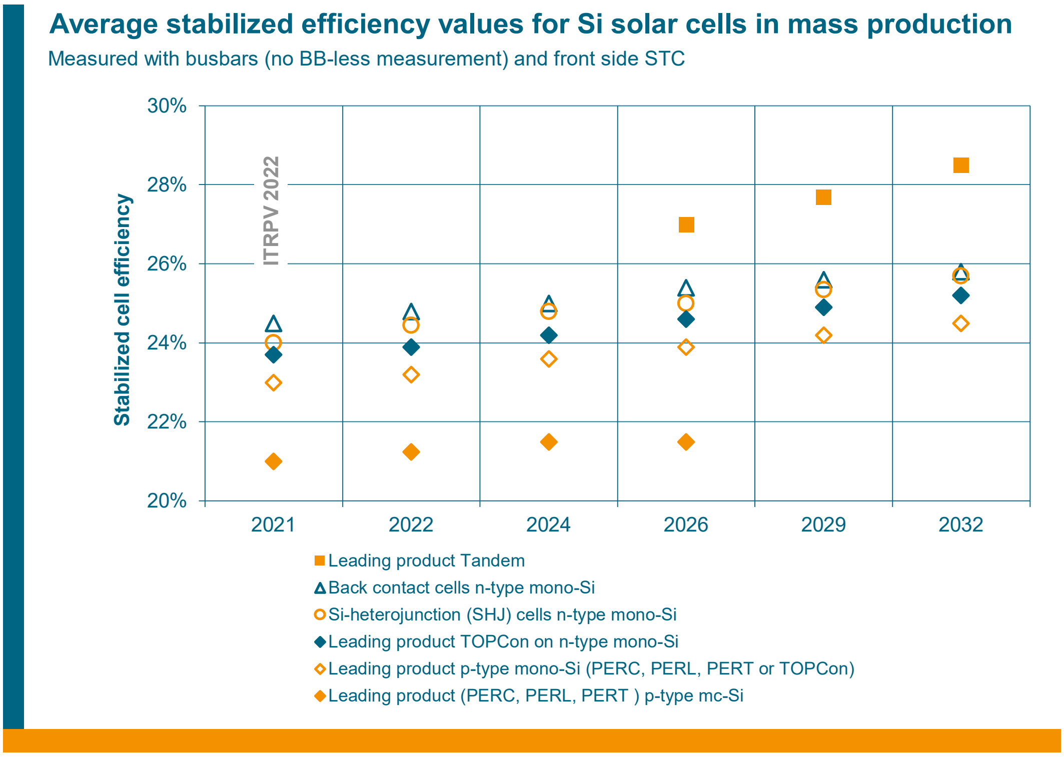


Fig. 34: Average stabilized efficiency values of c-Si solar cells in mass production.

Cells using n-type material show the highest efficiency potential of today's cell technology concepts. We found that p- and n-type mono-Si cells with diffused pn junction at the front side will reach up to 24.5% and 25% respectively in the next 10 years. Cells on n-type using tunnel oxide passivated contacts at the rear side show higher efficiencies than all p-type cell concepts as shown in Fig. 34. Other n-type-based cell concepts like SHJ and back-contact cells, will reach higher efficiencies of up to 25.7% in mass production within the next 10 years. We nevertheless see that the Si-based single junction cell concepts are converging to a practical efficiency limit of about 26%, close to the theoretical upper limit of 30% [26]. Tandem cells will overcome this limit. Mass production cell efficiencies of Si based tandem cells concepts are expected to start at about 27%. The introduction in the market is expected after 2024 according to Fig. 31.

Fig. 35 shows that new built cell production facilities will make use of the economy of scale by increasing their annual production capacity. Factories with > 2GW are dominating the manufacturing landscape today and fabs with > 5GW annual cell production capacity will dominate the production landscape for new cell production capacities and on the long run.

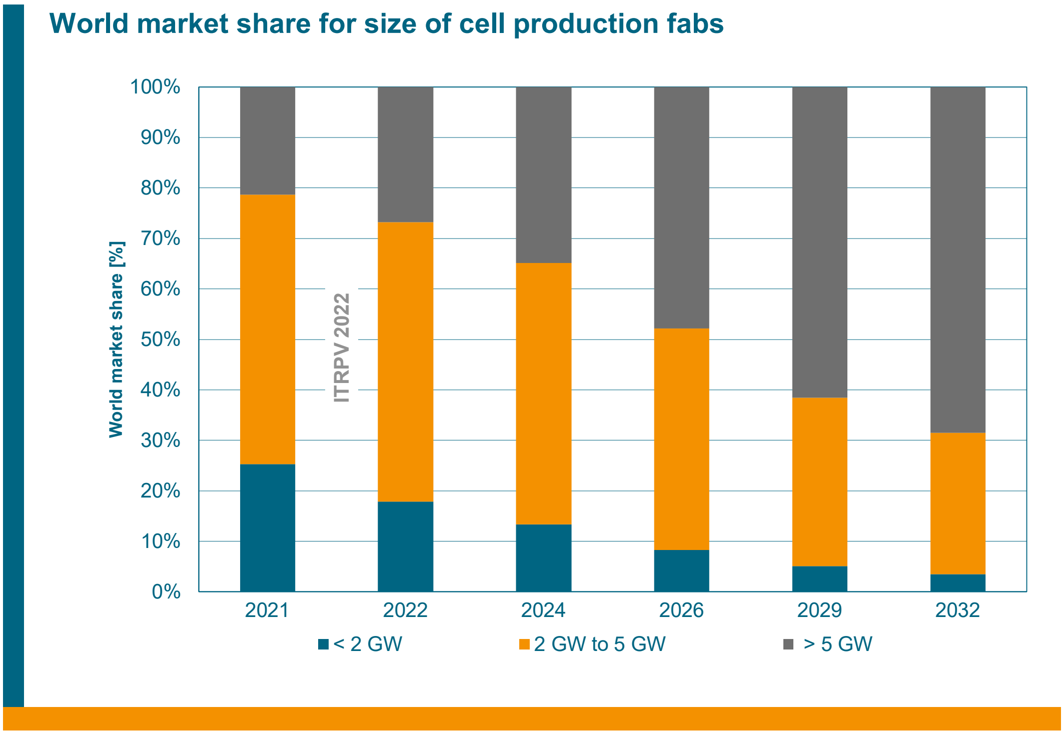


Fig. 35: Trend for name plate capacity of cell manufacturing fabs.

7. Results of 2021 | Module

7.1. Materials

Fig. 2 showed the price shares for mono-Si module products. The module related price share contributes with ≈ 50% to the module sales price. Cells are still the most expensive individual part of the module's bill of materials (BOM). The introduction of new, larger cell formats enables higher module powers and advantages in module efficiency at the expense of increased module size. Module conversion costs are dominated by material costs. Improvements of the module performance and of material costs are therefore mandatory to optimize module costs. Approaches for increasing performance like the reduction of optical losses (e.g., further reduced reflection of front cover glass), reduction of resistance loss, and the reduction of interconnection losses will be discussed in chapter 7.2. Approaches for reducing material costs include:

- Reducing material volume, e.g., material thickness.
- Replacing (substituting) expensive materials.
- Reducing waste of material.

All non-cell module materials contribute to module manufacturing cost with a similar portion. Glass is the most massive material of a module. It determines weight and light transmission properties. The thickness is also important for the mechanical stability of the module. Glass is used in standard modules as front side cover, in glass-glass modules, especially for bifacial applications it is used as front as well as back side cover. Fig. 36 summarizes the trend of front side glass thickness.

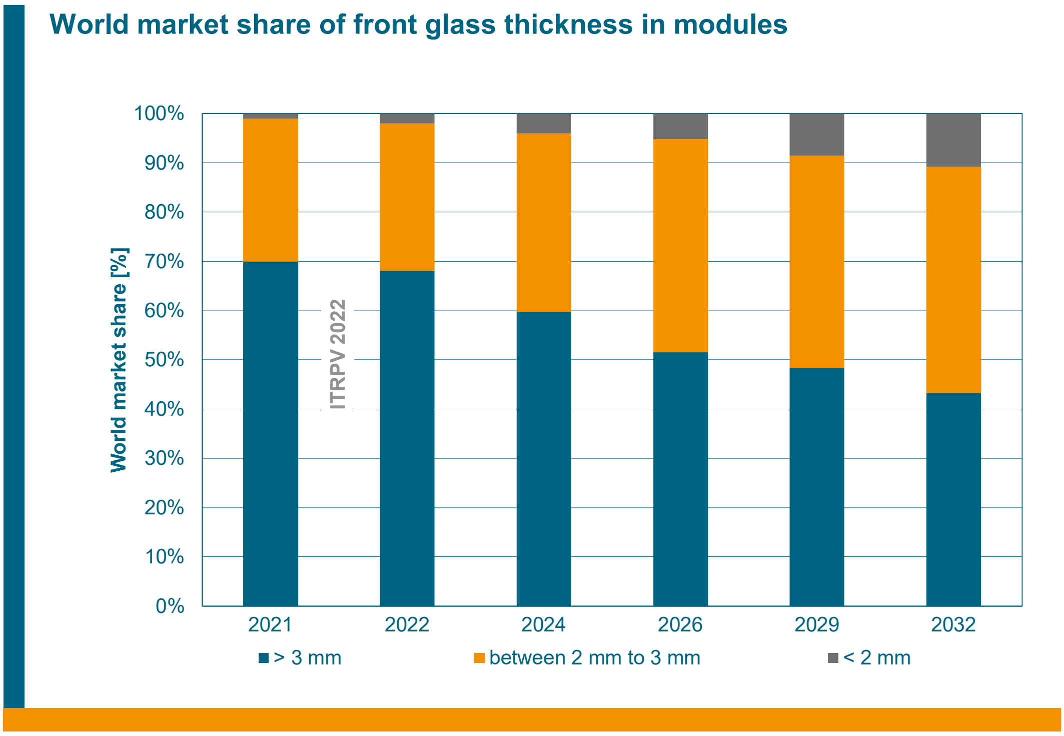


Fig. 36: Expected trend of front glass thickness in c-Si modules.

A thickness above 3 mm is mainstream. It is expected that a reduction towards 2 mm thickness will appear over the next years. A thickness below 2 mm is seen in the market with close to 1% even today with increasing share over the next years.

Rolled, structured glass is mainly used in today's module manufacturing. The float glass market share of about 7% in 2022 will grow to about 12% within the next 10 years as shown in Fig. 37.

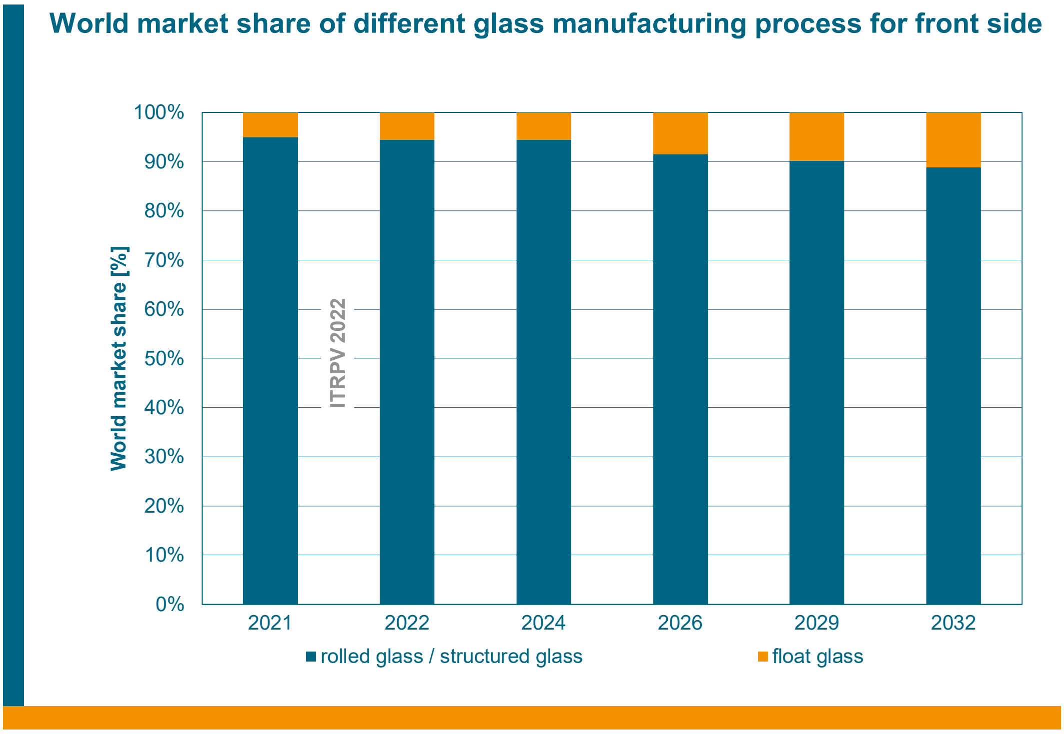


Fig. 37: Trend of front glass material market share.

Back side glass thickness is thinner as front side glass. Mainstream thickness is between 2 mm and 3 mm. Thickness below 2 mm is expected to appear in the market after 2022 according to Fig. 38.

Rolled, structured glass is dominating the back side glass market today but it is expected that after 2024 float glas will become more used with a share of about 65% in 2032 as senn in Fig. 39.

The use of antireflective (AR) coatings has become standard to improve the transmission of the front cover glass. AR-coated glass will remain the dominant front cover material for c-Si PV modules in the future, with market shares about 90%. Coatings for special applications like anti-soiling, anti-glare, color coating, or structuring as well as no coating at all are expected to keep a small market share between 1% and 3% per application.

The transmission of AR coated glasses appears to be today around 94.5%, about 3% higher than for non-coated glasses. A continuous improvement of the glass is expected to reach up to 95% transmission within the next 10 years. Since AR-coated glass will be the most used front cover, it is important that the AR coating remains effective and stable under various outdoor conditions during the entire operational life of the module.

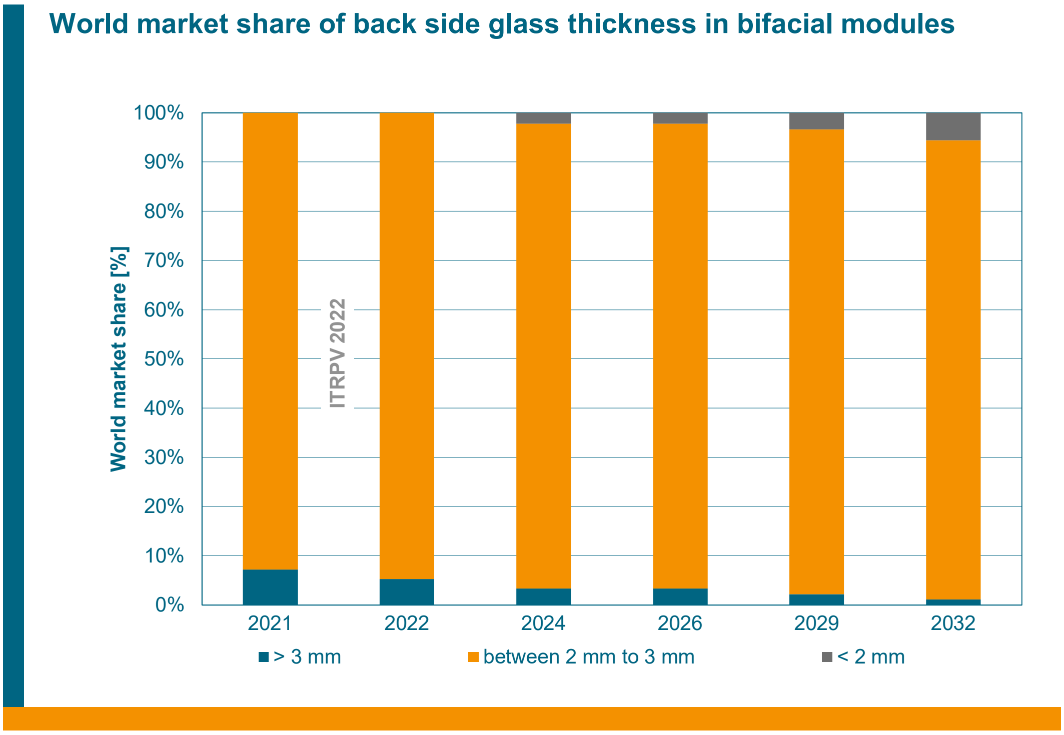


Fig. 38: Expected trend of back side glass thickness in in bifacial modules.

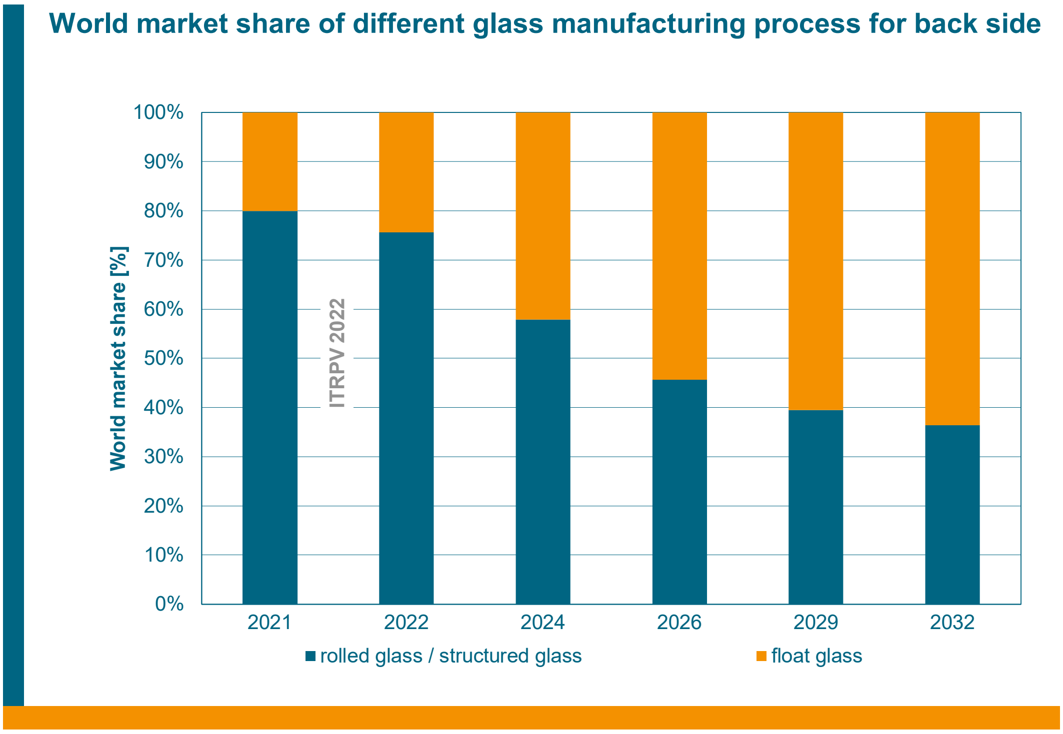


Fig. 39: Trend of back side glass material market share.

All AR coatings on the market meet an average lifetime of at least 15 years, and there is a clear trend indicating that the average service life of these coatings will improve to 25 years until 2029.

Today, solders that contain lead are the matured standard technology for reliable and cost-efficient interconnection of double-sided contact Si solar cells and for module interconnection in the module manufacturing process. Lead-free interconnection alternatives exist for special application and cell concepts like SHJ cells and IBC. Fig. 40 and Fig. 41 show the expected market share trends of different technologies for cell interconnect and for string interconnection within the module respectively. Lead containing soldering is the expected mainstream technology for the next 10 years.

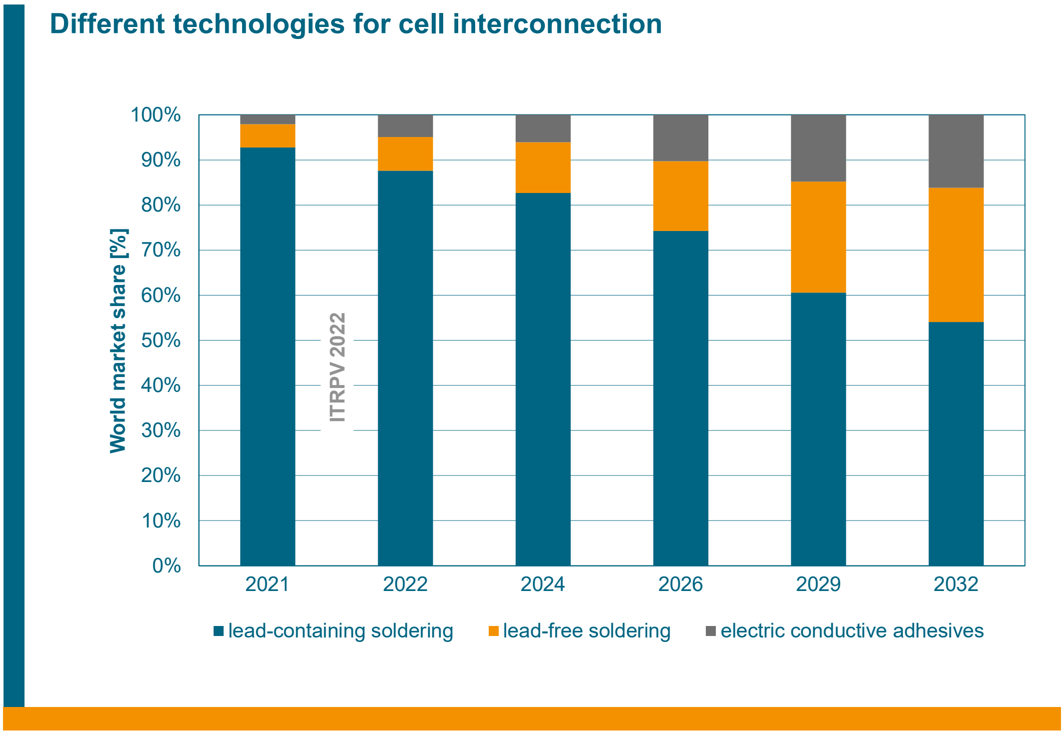


Fig. 40: Expected market share for different cell interconnection technologies.

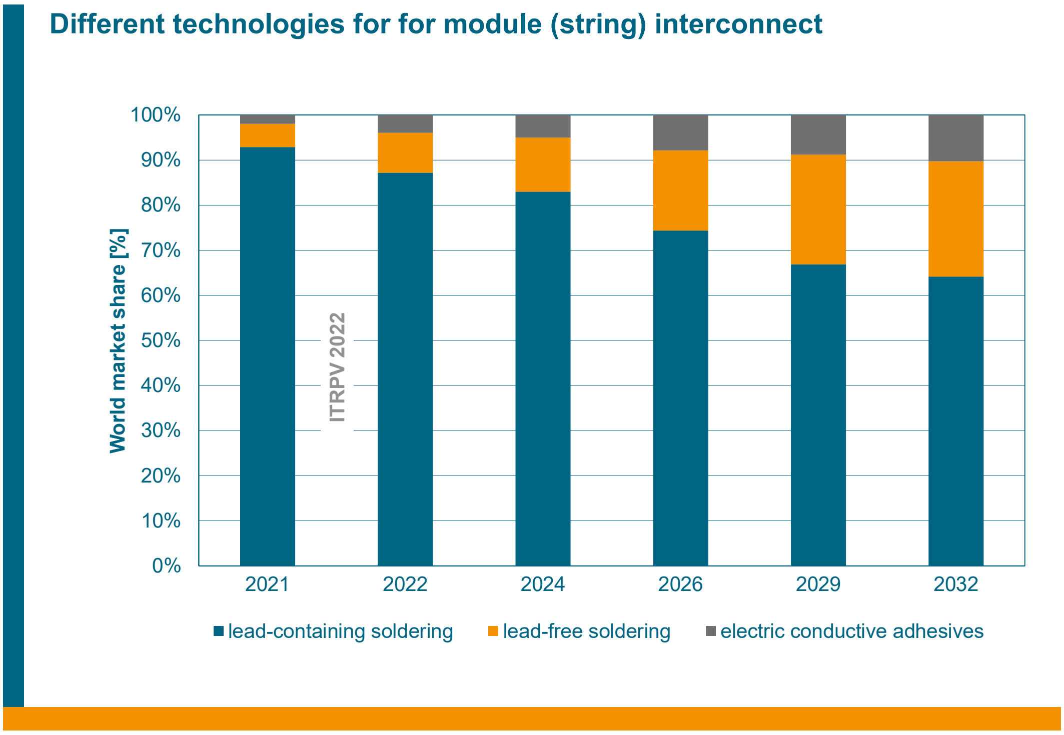


Fig. 41: Expected market share for different module interconnection technologies i. e. for string interconnection.

Conductive adhesives are expected to gain market share from about 5% in 2022 to over 15% within the next 10 years. Lead free soldering, mainly driven by SHJ, is expected to gain market share from 6% in 2022 to well above 20% in 2032.

Materials containing lead are restricted in accordance with legislation that went into effect in 2011 under the EU Directive on the Restriction of Use of Hazardous Substances (RoHS 2) [27]. This restriction affects the use of lead and other substances in electric and electronic equipment (EEE) on the EU market. It also applies to components used in equipment that falls within the scope of the Directive. PV modules are excluded from RoHS 2, meaning that they may contain lead and do not have to comply with the maximum weight concentration thresholds of 0.1% as set out in the directive.[1] PV's exclusion and the thresholds will surely remain in effect until the ongoing review process of this directive will have been finished in the 2022/2023 timeframe.[2]

Cell and module manufacturers should act carefully, especially, as the exclusion to the defined threshold in question is limited to PV panels installed in a defined location for permanent use (i.e., power plants, rooftops, building integration etc.). Should the component in question (the module) also be useable in other equipment that is not excluded from RoHS 2 (e.g., mobile charging applications), then the component must comply with the Directive's provisions at this stage.

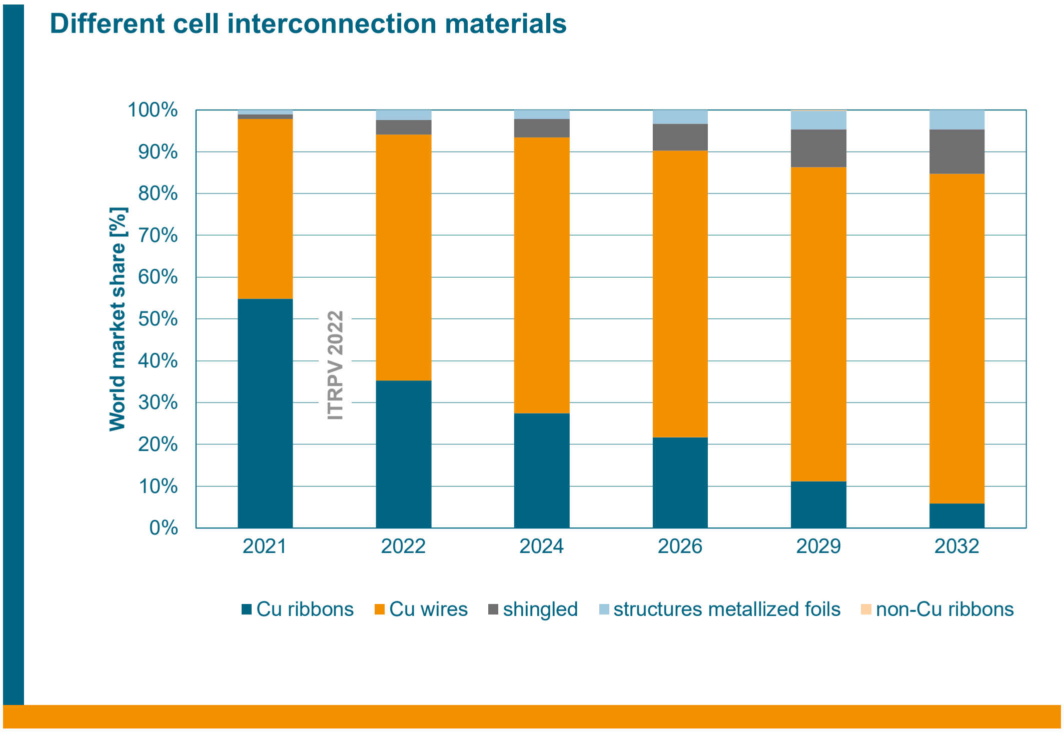


Fig. 42: Expected market shares for different cell interconnection materials.

Fig. 42 shows that copper ribbons have lost since 2022 their dominating position as material for cell interconnection. Copper wires have been gaining share and are dominating the interconnection technology from 2022 onwards, fired by the success of half-cell technology. Within the next 10 years, overlapping interconnect technologies and structured foils will gain market share to about 10% and close to 5% respectively. Non-Cu-based ribbons will appear after 2025 as a niche.

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[1] Article 2(i) of the RoHS Directive [2011/65/EU] excludes from the scope of the Directive "photovoltaic panels intended to be used in a system that is designed, assembled and installed by professionals for permanent use at a defined location to produce energy from solar light for public, commercial, industrial and residential applications."

[2] Article 24 of the RoHS Directive [2011/65/EU] requires an evaluation and possible revision of the Directive, including its scope, by July 2021.

It is important to note that the existing and upcoming interconnection technologies will need to be compatible with the all cell formats and upcoming cell technologies. In this respect, low-temperature approaches using conductive adhesives or wire-based connections have an inherent advantage due to the lower thermal stresses associated with them.

In Fig. 43 we see how module technology will be capable to process thinner cells as discussed in chapter 5.3. Cell thickness reductions, according to Fig. 7, Fig. 8, and Fig. 9, will not be limited by module technology. So, Si material savings may and will contribute to future Wp cost reductions.

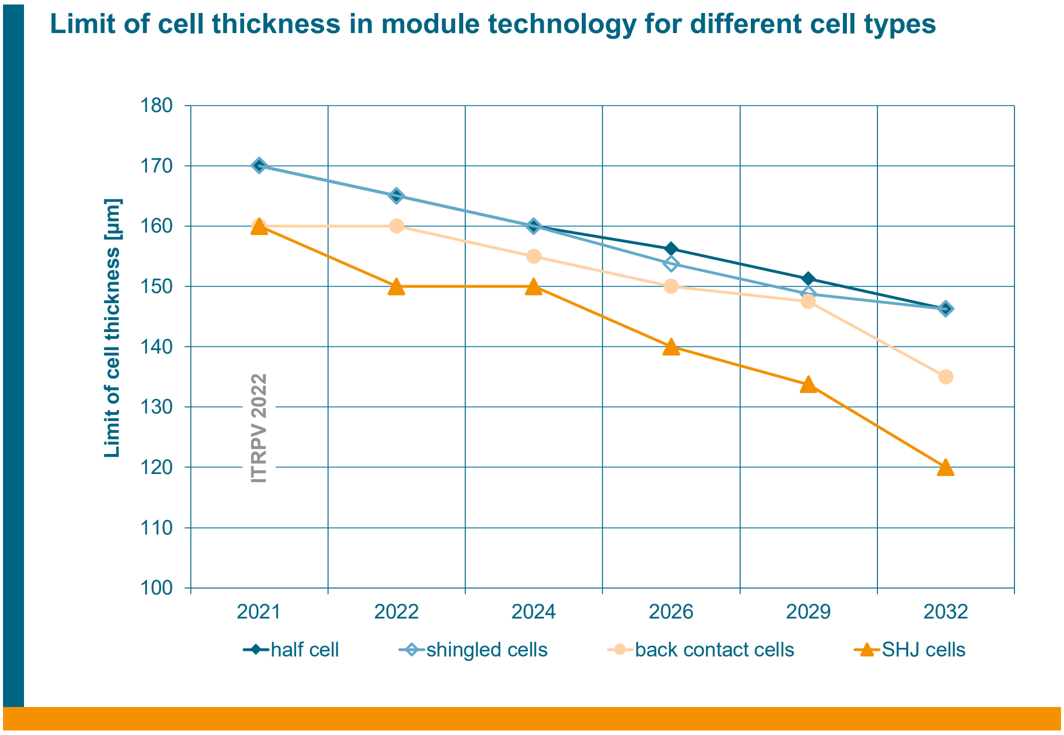


Fig. 43: Predicted trend of cell thickness limit in different module technologies.

The encapsulation material and the back sheet / back cover materials are key module components to ensure long time stability. Both are also major cost contributors in module manufacturing. Intensive development efforts have been made to optimize these components regarding performance and cost. Improving the properties of this key components is mandatory to ensure the module service lifetime. EVA will stay the most widely used encapsulation material for PV modules as shown in Fig. 44. White EVA is expected to keep a quite constant market share of about 10% over the next years. Polyolefins are an upcoming alternative especially for bifacial products in glass-glass combination and for SHJ [28]. We expect an increasing market share for Polyolefins of close to 20 within the next 10 years. Other materials are expected to keep low market share for niche applications.

Different encapsulation material

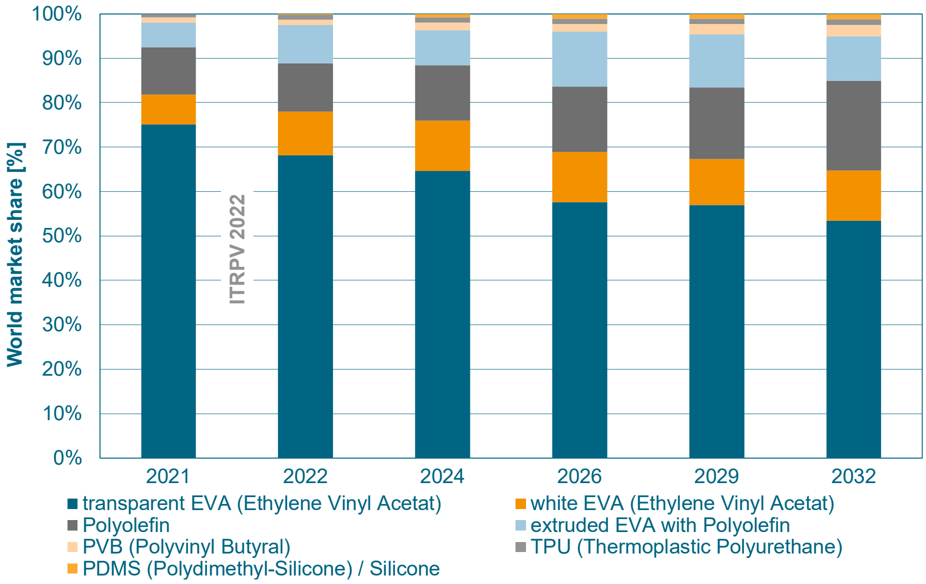


Fig. 44: Market share for different encapsulation materials.

As can be seen in Fig. 45, foils will stay mainstream as back cover material, but glass is expected to gain a significant higher market share as backside cover material especially for bifacial c-Si module applications: glass as rear side cover is expected to have about 45% share in 10 years. Foil as front side cover will stay a niche. The thickness of the back glass is expected to stay in the range between 2 mm and 3 mm as shown in Fig. 38.

World market share of different front and back cover materials

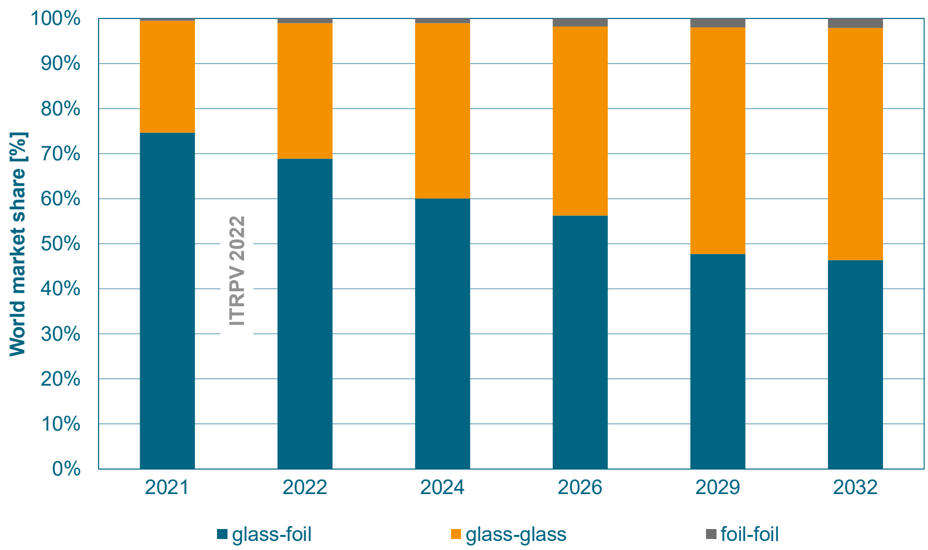


Fig. 45: Market share of glass and foil as front and back cover.

Fig. 46 summarizes the expected share of common backsheet material compositions. Polyethylene Terephthalate (PET) will stay in use as core layer for most of backsheet compositions as it provides good electrical insulation and protection against moisture. It is cost effective to produce. Numerous products use therefore PET as core layer, sandwiched between UV-protection layers [28]. Polyolefin core based backsheets will slightly increase their market share, Foils using Kynar (PVDF) at the air side are expected to keep the largest market share. Foils using Tedlar will have market shares around 20%. Several new materials are expected to appear.

The mainstream color of the backsheet foils will stay white. Black colored backsheets will stay at a stable level around 10% - especially for roof top applications. Transparent backsheets are considered as an upcoming trend for bifacial cell applications as cost and weight efficient alternative to glass.

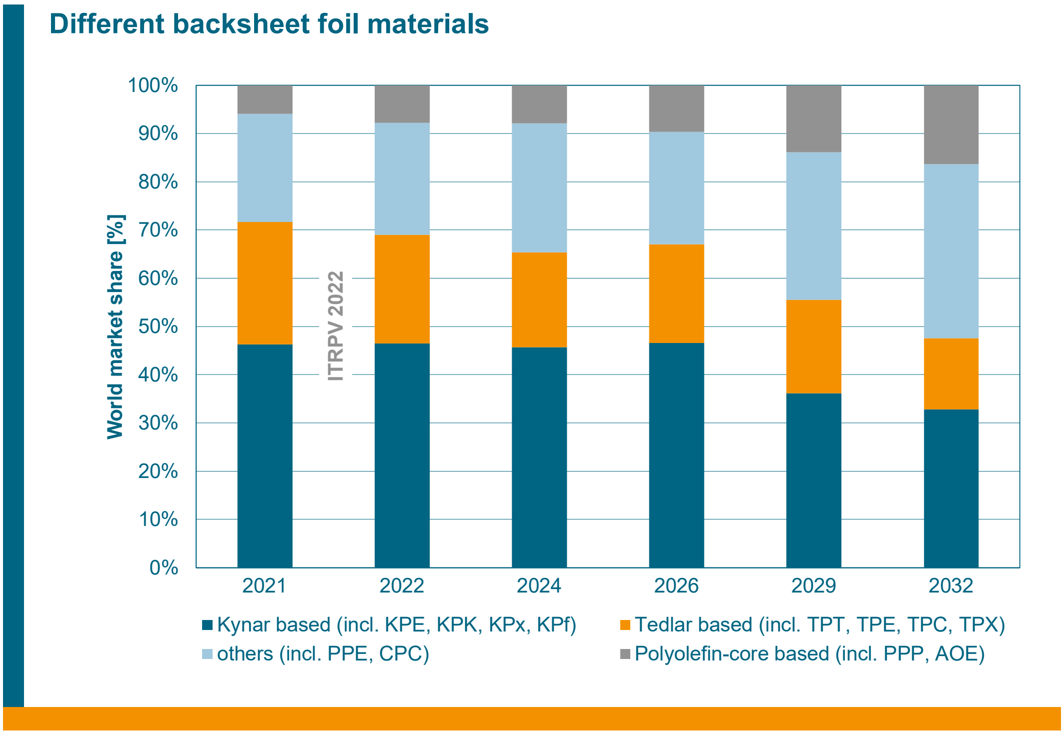


Fig. 46: Back cover foil materials trend: foils with PET core will stay dominant.

Fig. 47 looks at the trends for frame materials. Modules with aluminum frames are clearly dominating the market. Frameless modules are expected to increase its market share to about 15%. Plastics are considered as niche application with market shares of ≤ 5%.

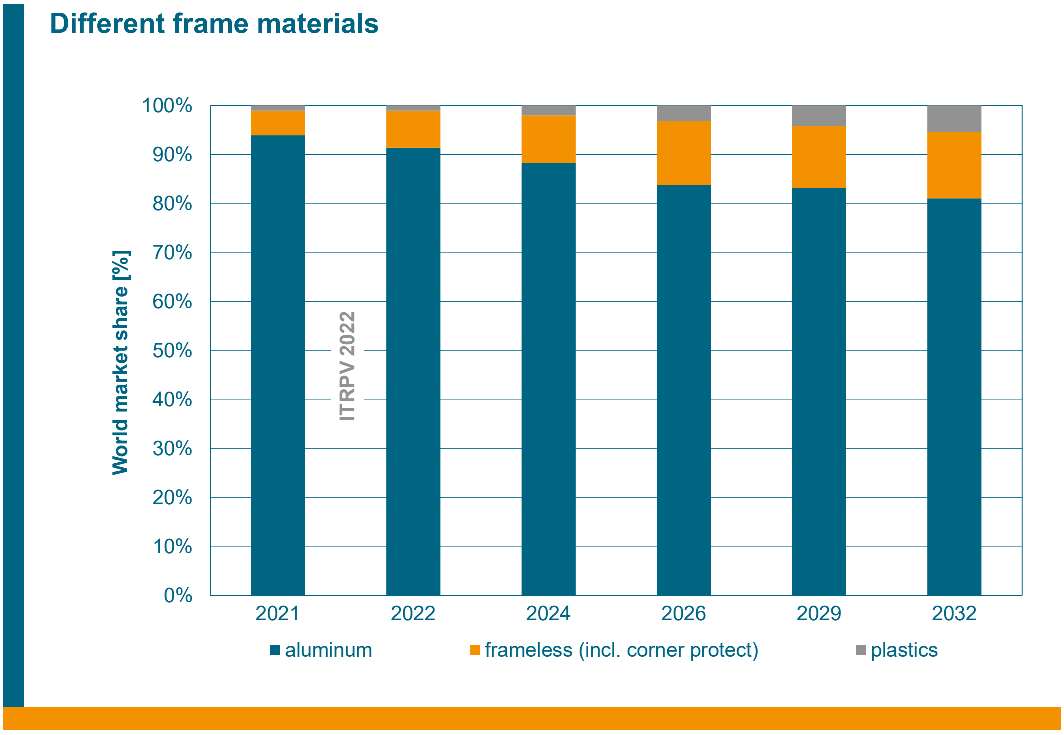


Fig. 47: Market shares for frame materials.

7.2. Processes

It is crucial to get as much power as possible out of the assembled solar cells. The cell-to-module (CTM) power ratio is a parameter to monitor this behavior. It is defined as module power divided by cell power multiplied by the number of cells (module power / (cell power x number of cells)).

The biggest process change in module design during the last years was the introduction of half cells, in parallel with the introduction of wires instead of ribbons as described in Fig.42. The deployment of half-cells is the dominating mainstream today for cells < M10 as shown in Fig. 48a. Full cell technology market share will be reduced to below 5%. It will be used for IBC and in special module applications. third and quarter cells are for niche applications with a share of 1% only.

Cells ≥M10 are also using half cells mainly as the trend in Fig. 48b shows, full cells are not used in use for large wafers. Third and quarter cells will be deployed, especially for G12.

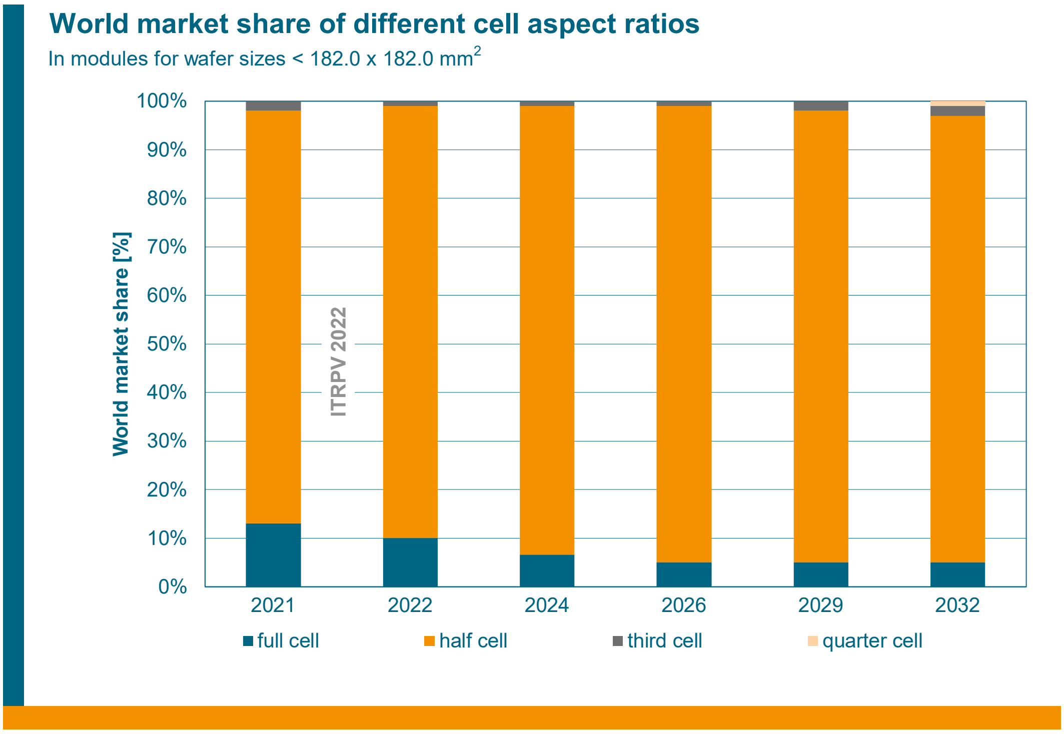


Fig. 48a: Market shares of modules deploying half, third, and quarter cells ≥M10.

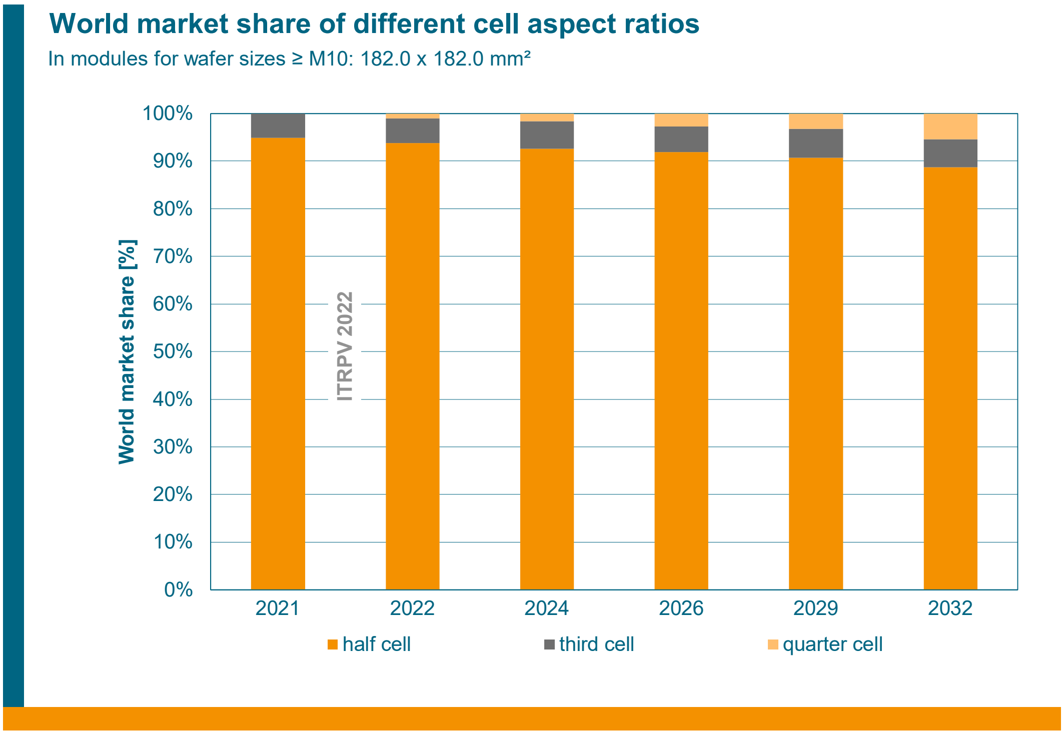


Fig. 48b: Market shares of modules deploying half, third, and quarter cells ≥M10.

Fig. 49 shows the CTM values for full-cells, half-cells, and third-cells. The CTM for full-cell modules was 2021 at 98.2% for mono-Si cell technology (alkaline texturing) and 100.5% for the corresponding half-cell modules. The introduction of new interconnection and encapsulation technologies (e.g., narrower ribbons, encapsulation materials with improved UV performance, etc.) will result in further improvements that will enable additional power gains but reduction of CTM. CTM, will stay a good parameter to monitor the process stability of the module production process.

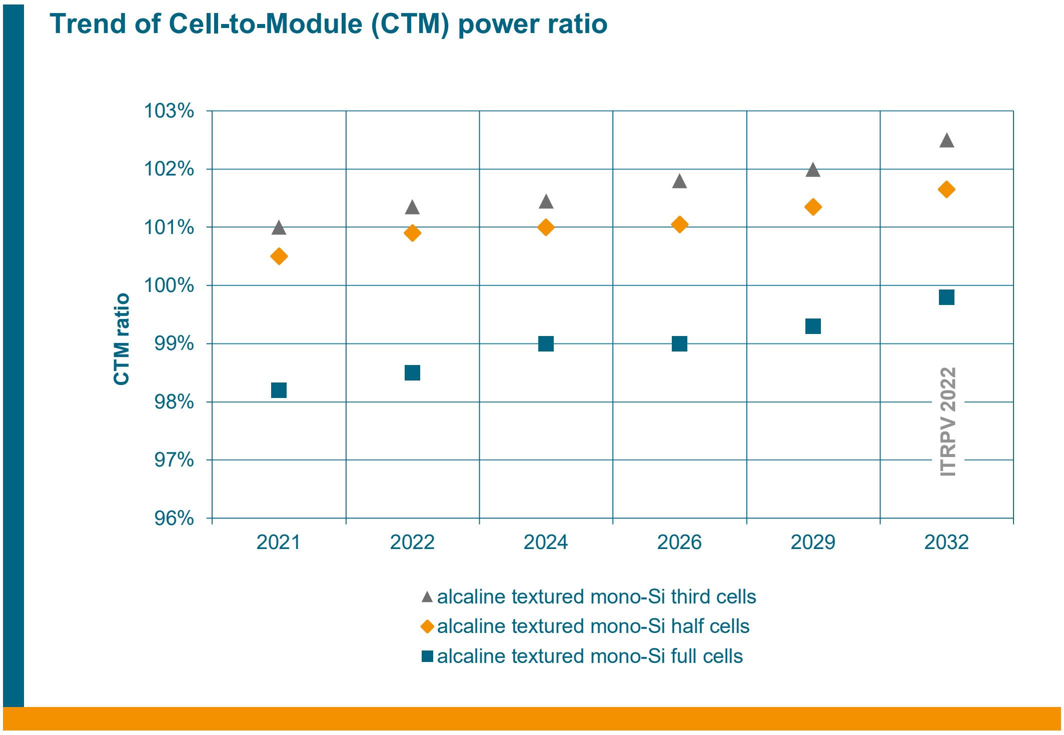


Fig. 49: Expected trend for the cell-to-module power ratio.

The trend for module production fabs is similar to the trend in cell production as shown in Fig. 50. Factories with annual capacities of > 5GW will dominate the future production landscape. Nevertheless, smaller module fabs with < 5GW, and also < 1GW are expected to be present for special applications and for special, as well as for regional markets.

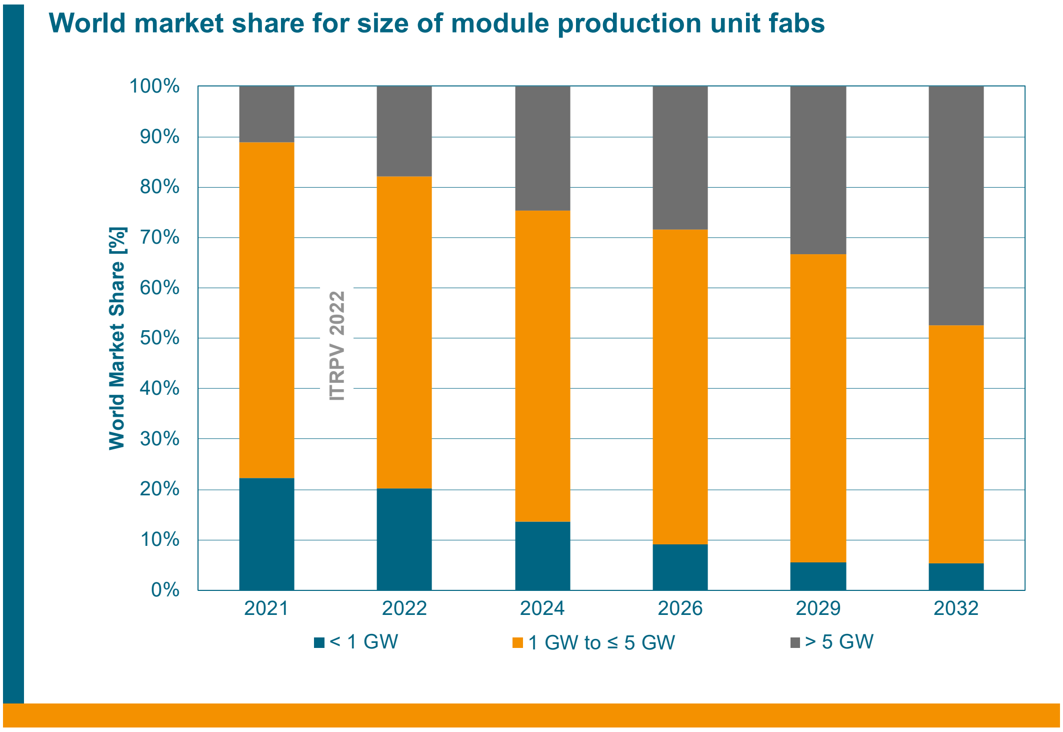


Fig. 50: Trend for name plate capacity of module manufacturing fabs.

7.3. Products

Due to the current diversification in wafer formats as discussed in chapter 5.3., also module dimensions are changing. Comparing different module types only by the so far common module label power may be misleading as module powers with ≥ 600 Wp are possible with existing cell technologies [28, 29]. Therefore, the module efficiency is a useful parameter to compare different technologies and the final products. Module efficiency is calculated with module label power divided by the product of module area in m² and the irradiance at standard test conditions (1000W/m²): (module label power / (module area x 1000 W/m²)). In today's module data sheets, the module efficiency is indicated - a value of 20% corresponds to a module area efficiency of 200 W/m². Fig. 51 shows the expected trend of average module efficiency for modules in mass production with different cell technologies.

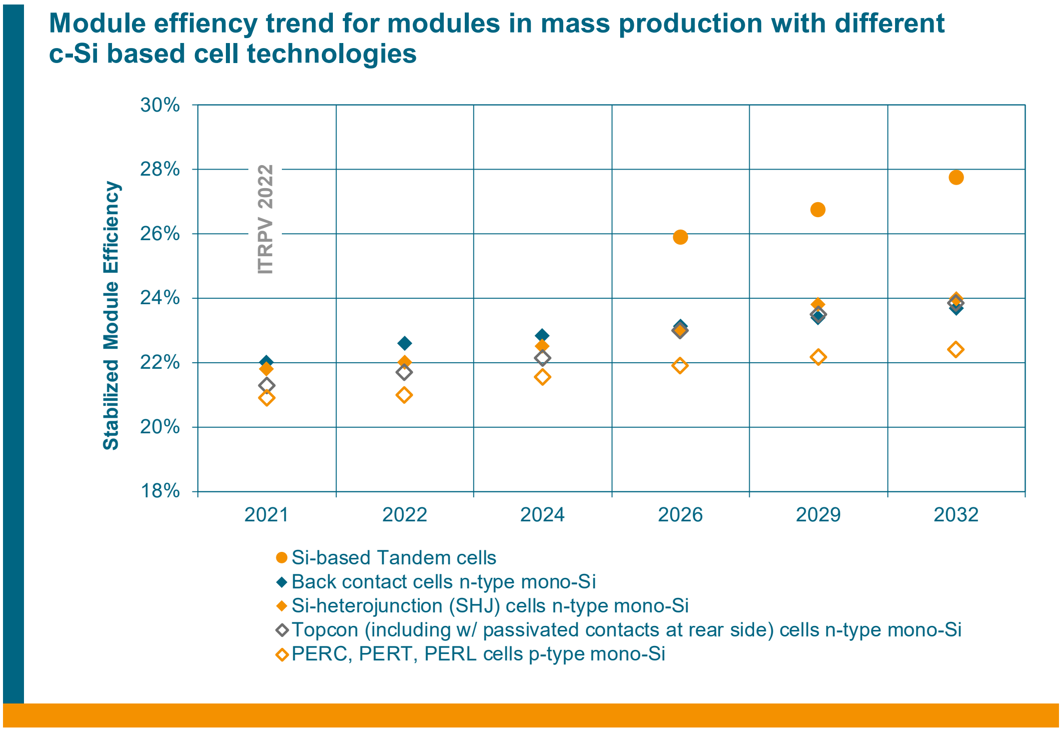


Fig. 51: Average module area efficiency in mass production for different c-Si solar cell technologies.

Current PERC p-type mono-Si modules are expected to show average efficiencies of 21% in 2022 and up to 22.5% within the next 10 years. Modules with n-type cell with tunnel oxide passivation technologies, are expected to be ahead of p-type PERC with 21.8% in 2022 and with up to 24% in 10 years. SHJ modules reach in 2022 22% and are expected to yield also with 24% in 2032. Back-contact cells on n-type are expected to show again the highest module efficiencies in 2022 but are expected to be in a same range with all n-type cell-based modules. We also report expected efficiencies for modules deploying Si-based tandem concepts. Si-based tandem modules are expected after 2024 with module efficiencies of 26% in 2026 and with close to 28% in 2032, respectively.

In the past, two form factors were present in c-Si module products: 60 cells/120 half cells and 72 cells/144 half cells. Fig. 52 shows that the 2022 module market based on < M10 cells, splits still into these two groups: about 30% for 120 half-cell and 45% 144 half-cell modules. During the next 10 years 120 form factor share will shrink to about 15% while the share of 144 will grow to 55%. The full cell form factors are still listed but are in the phase out as discussed in 7.2. Modules with up to 132 half cells are used in roof top application, 144 half cells and more are for power plant use. G12 cells are mainly used with new form factors for highest power class modules, good for power plants [30]. M10 format is also used in the half cell form factors of 108, 132, 144, and 156 [29].

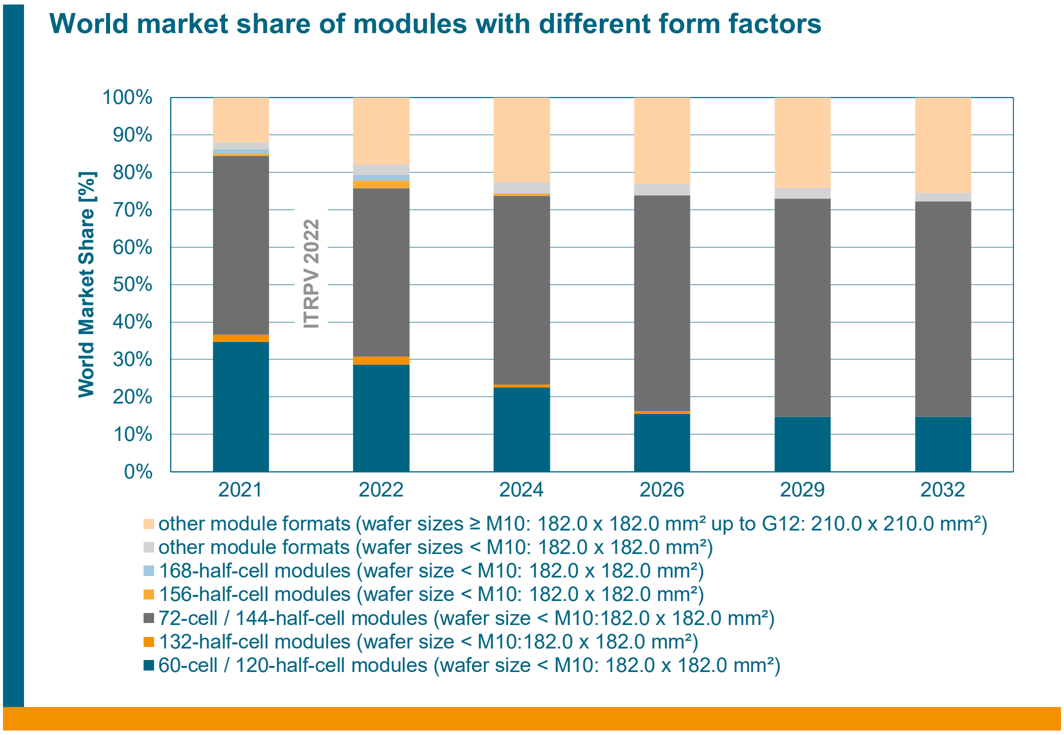
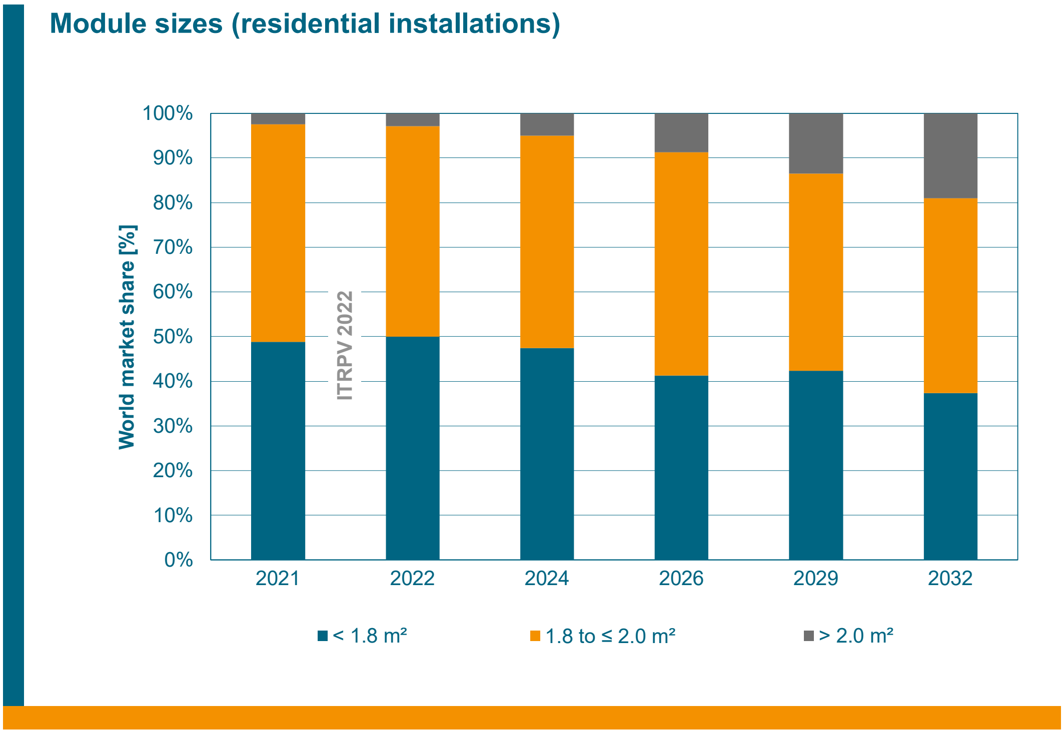


Fig. 52: Market share for modules with different formats.

The big variety of form factors leads also to various module sizes. Fig. 53 shows the trend of module size for residential applications – module size will increase beyond 1.8m²: in 2022 modules < 1.8m² account for 50%. This share will shrink to 38% within the next 10 years. Modules with a size between 1.8 m² and 2.0m² will keep a share around 45%. Modules >2m² are expected to increase market share to 20%.



Fig, 53: Trend of module size for roof top applications.

The trend of module size for large size modules, especially deployed for power plants is visualized in Fig. 54. The trend to larger modules is more significant in this field. Module sizes up to 3 m² will be dominating the power plant market from 2022 onwards – and larger modules >3 m²are expected to gain share to at least 15%.

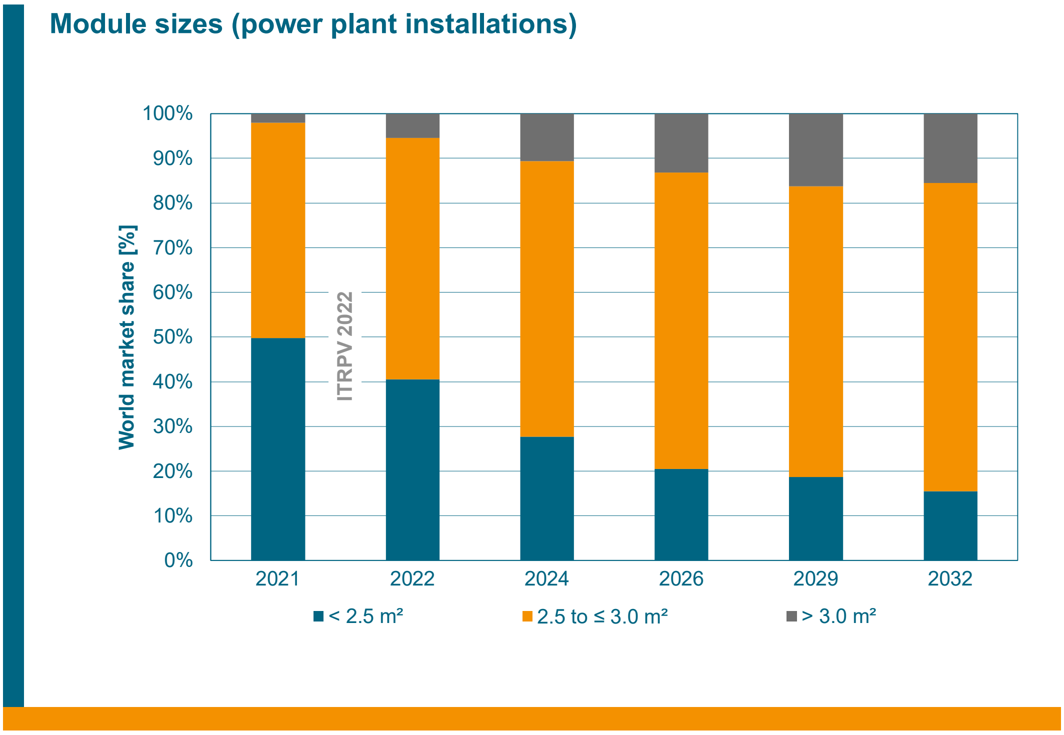


Fig.54: Trend of module size for power plant applications.

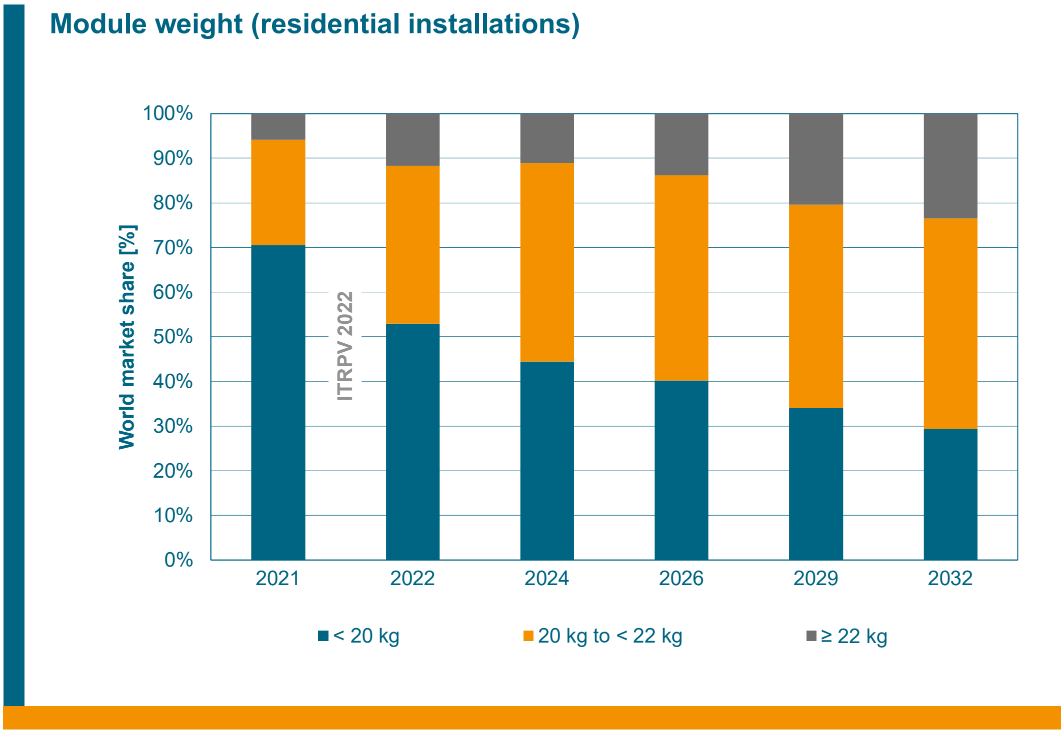


Fig. 55: Market share for the weight of modules for residential applications.

Larger modules will be weighted further. Fig. 55 and Fig. 56 show the expected trend of module weight for residential and for power plant installations, respectively.

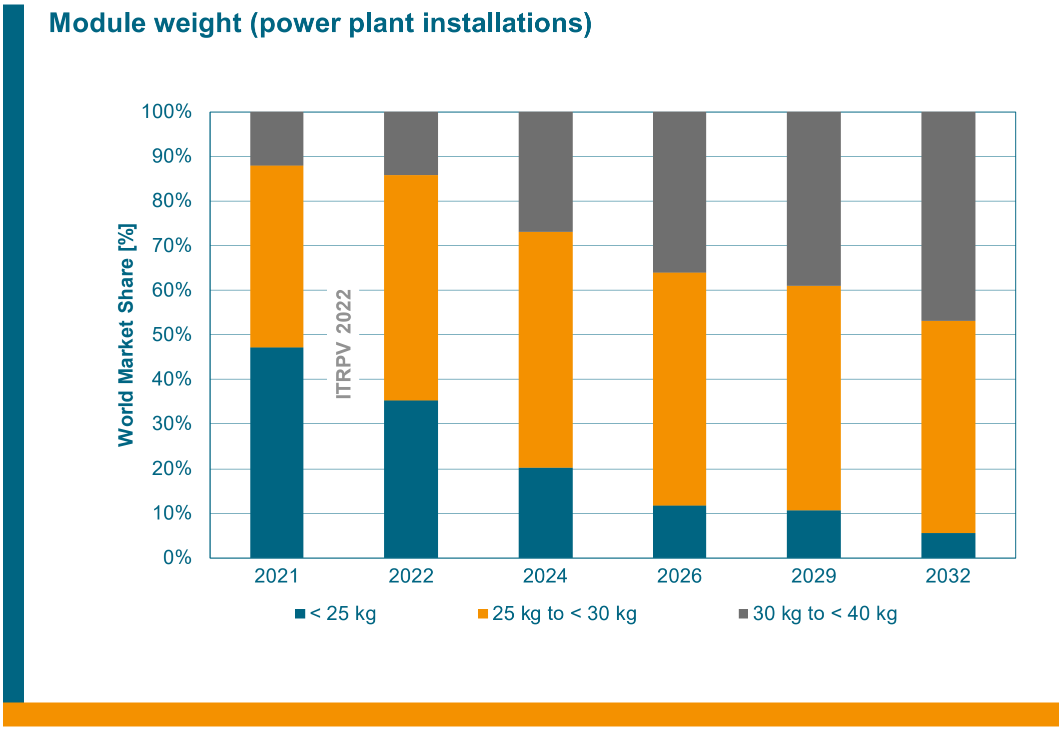


Fig. 56: Market share for the weight of modules for power plant applications.

Today, still most of modules are monofacial modules – in 2022 about 70% as shown in Fig. 57. Anyhow, bifacial modules share will grow to about 60% within the next years. Bifacial cells can be used in bifacial modules as well as in conventional monofacial modules. Bifacial cells will gain market share as discussed in chapter 6.3 and as shown in Fig. 33. We expect that between 20% and 30% of bifacial cells will be used in monofacial modules. Bifacial modules will mainly be deployed in power plant installations.

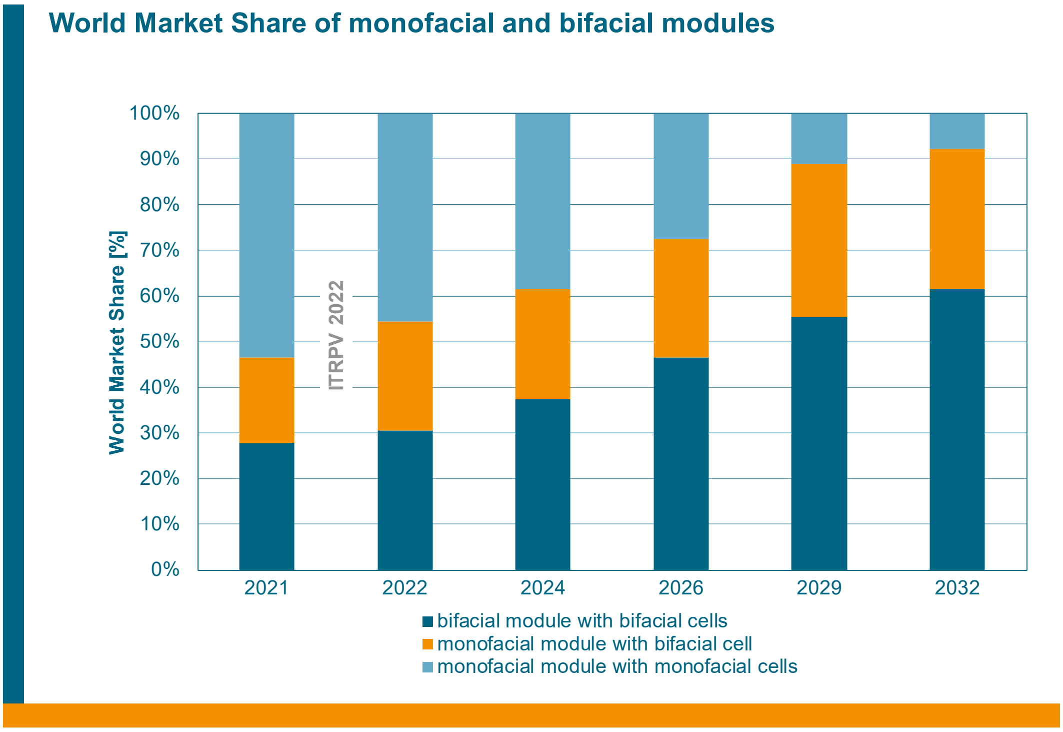


Fig. 57: Market share of bifacial modules.

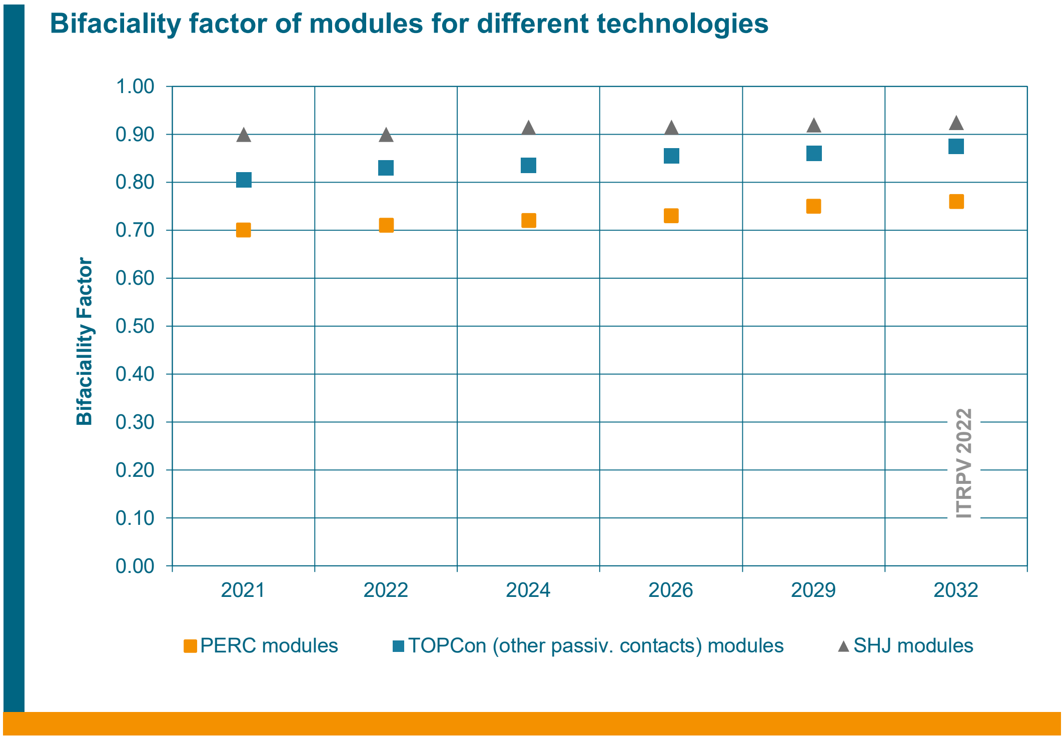


Fig. 58: Trend of bifaciality factor for modules with different cell technologies.

An important parameter to characterize the performance of bifacial modules is the bifaciality factor. It describes the ratio between rear-side and front-side efficiency, measured under STC (standard test conditions). Fig. 58 shows the bifaciality factors of modules with different cell technologies. We see, that SHJ cells have the highest bifaciality factor that is expected to improve to up to 0. 92. The bifaciality factor of standard PERC cells is expected to improve from about 0.7 in 2021 up to 0.76 within the next 10 years. Topcon cells show a bifaciality in between SHJ and PERC.

Another trend in module technology is the development of modules for special markets and environmental conditions. Fig.59 shows the assumed market share of modules for special environmental conditions. It is still expected that the main market will be for standard modules. Modules for special environmental conditions like tropical climate, desert environment, or floating will together account for up to 20% over the next 10 years.

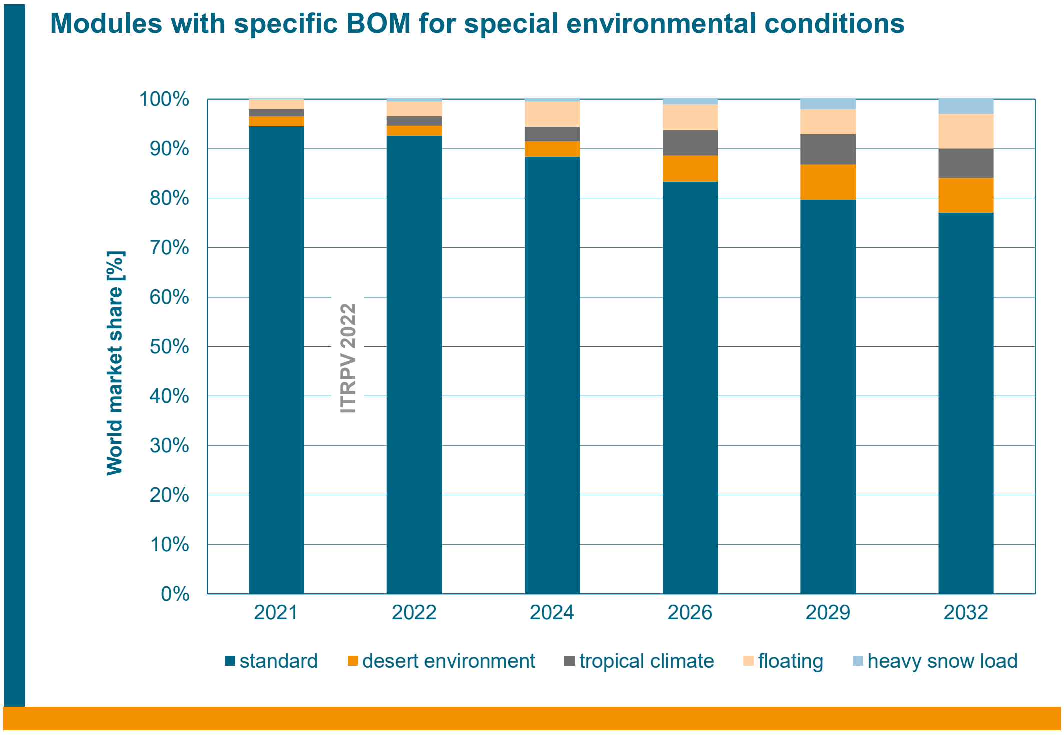


Fig. 59: Market share for special regional applications.

The junction box (J-box) is the electrical interface between the module and the system. Multiple junction boxes will stay the dominating J-Box concept boosted by the success of half-cell module concepts. We found that the internal electrical connection of the bypass diodes is and will be done mainly by soldering. Welding is seen as possible alternative technology with constant 30% market share.

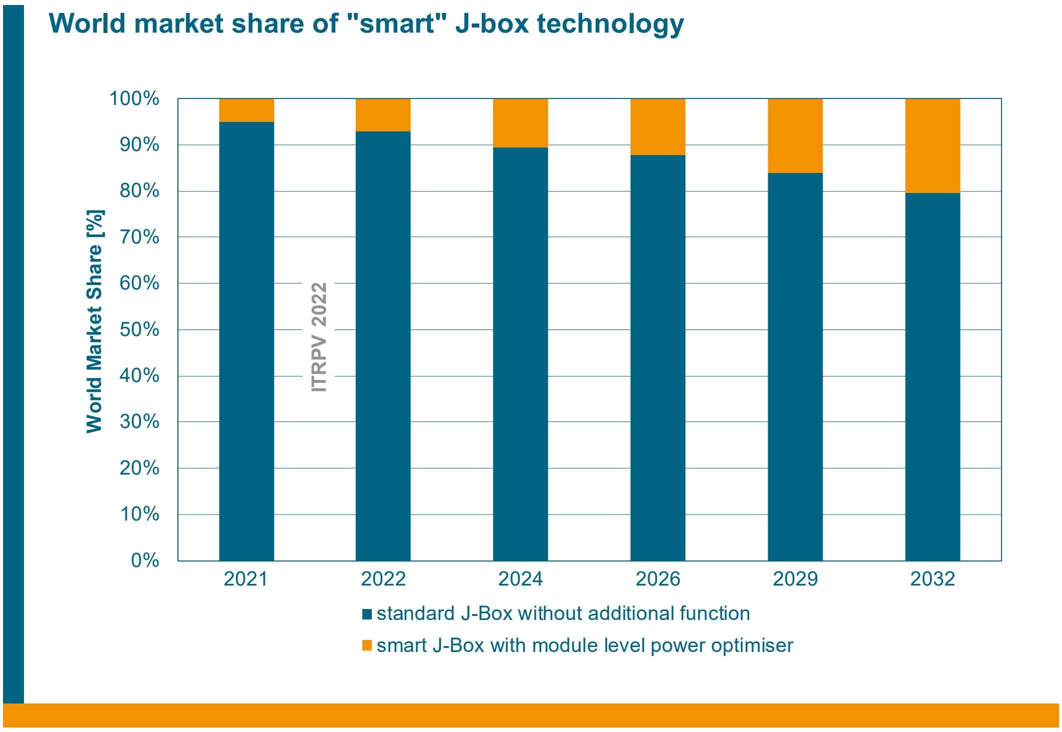


Fig. 60: Market share for different J-box functionality - smart vs. standard J-box.

So-called smart J-box technologies are deployed to improve the power output of PV systems and will increase their market share to about 20% within the next 10 years as shown Fig. 60. Nevertheless, the participants in our survey believe that standard J-box without any additional function except the by-pass diodes will clearly dominate the market.
The trend for J-box with special internal functions is shown in Fig. 61. Special features will be used in special markets. Standard junction boxes without additional functions will stay mainstream.

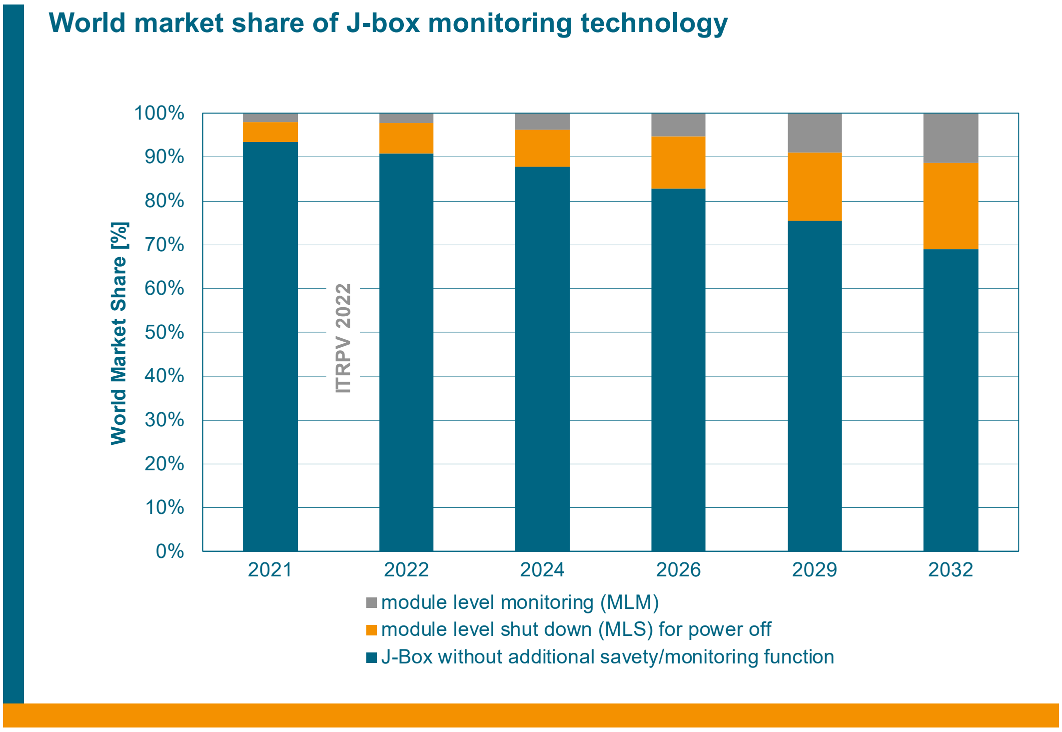


Fig. 61: Junction box monitoring technology.

Fig. 62 shows the estimated trend of warranty requirements and degradation for the next years. The product warranty is expected to increase from 12 to 15 years. Performance warranty is expected to increase to 30 years from today's 25 years. The degradation after the 1st year of operation will be reduced from 2% to 1%. This is mainly linked to the control of light induced degradation (LID) and to the light and elevated temperature induced degradation (LeTID). Understanding the degradation mechanisms and a tight control of the degradation are mandatory to ensure the warranty [18, 31]. The implementation of gallium doped wafers as discussed in chapter 5.2.1 and shown in Fig. 5 is supporting this trend. Standards for LeTID testing are about to be developed. Yearly degradation is expected to be reduced slightly from 0.6% in continuously to below 0.5% within the next 10 years.

In order to maintain quality (for thinner cells as well), the solar cells used for module assembly should be free of micro-cracks.

The contributors consider Potential Induced Degradation (PID)-resistant cell and module concepts also as market standard.

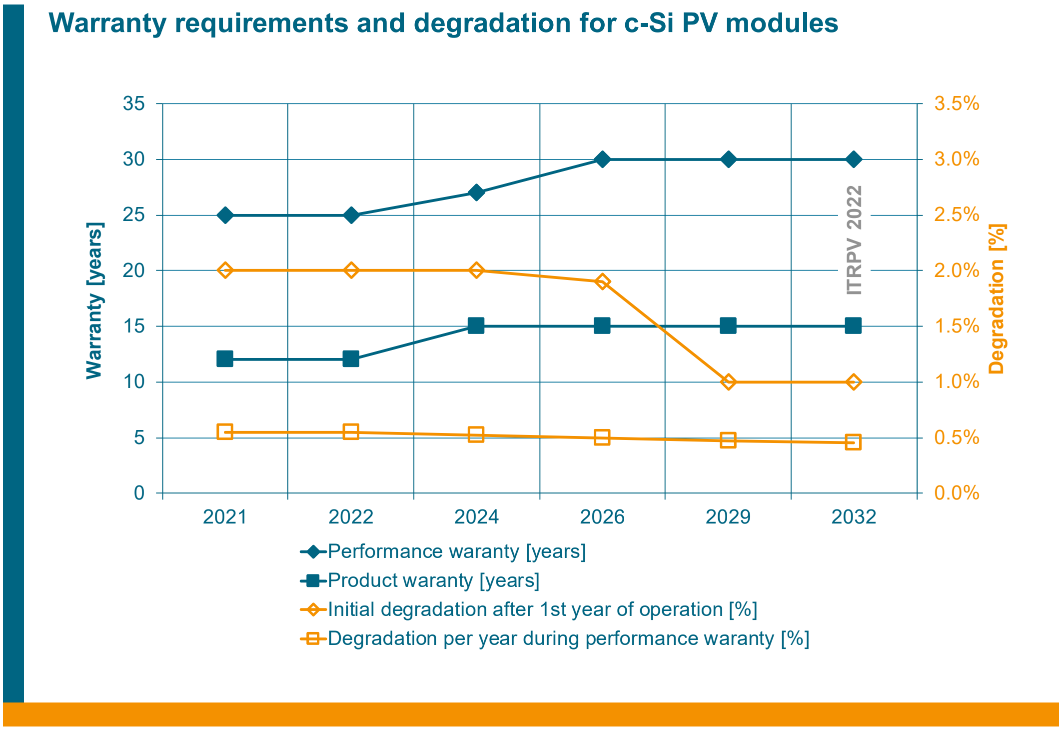


Fig. 62: Expected trend for product warranty and degradation of c-Si modules.

8. Smart Fab Status

Using the tools in an efficient way is mandatory to keep path with required cost reductions. Fig. 63 summarizes the status of Overall Equipment Efficiency (OEE) according to SEMI E10 [32] in state-of-the-art cell production facilities for different cell sizes. Tools for ≤ M6 appear to have higher OEE values over the tools for ≥ M10. Tools for larger wafers should demonstrate similar values like for the smaller to realize the full advantage of the higher productivity. So, process stabilization and tool improvements are required to close the gap.

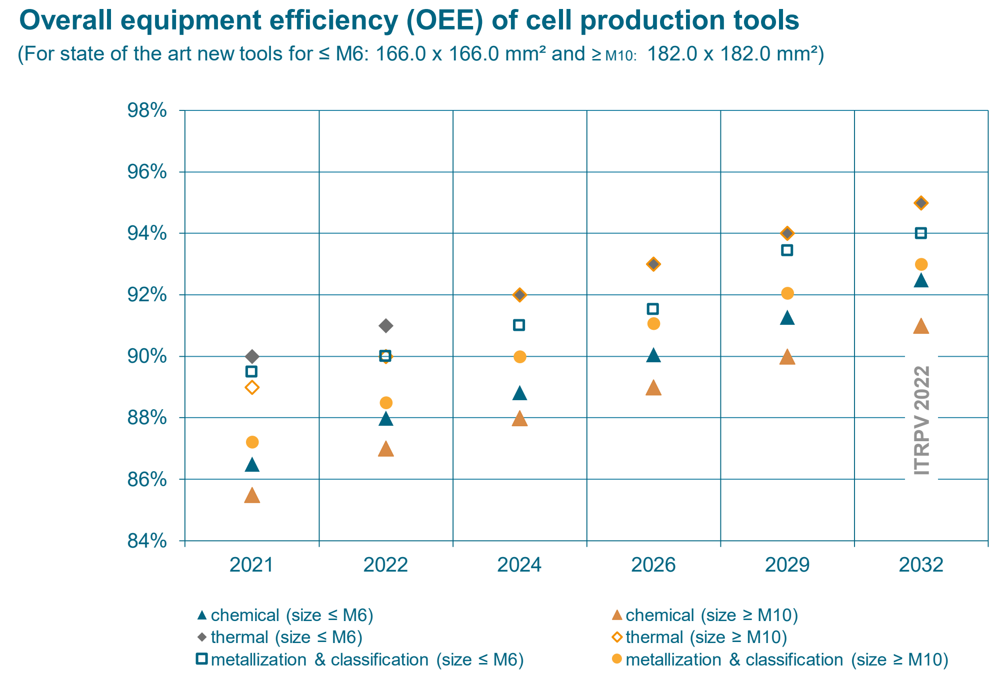


Fig. 63: OEE trend of state of the art new cell tools in new production facilities.

OEE Improvements will mainly be realized by improving tool and fab automation, automatic recipe downloads, via integration of the tools into Manufacturing Execution Systems (MES) and automatic dispatching systems as well as automated wafer-to-wafer and lot-to-lot process control systems. In addition, yield improvements for all tools have to be assured despite the introduction of larger and thinner wafer.

The trend for inline process control in cell and module production lines is shown in Fig. 64. To ensure high production yields and high average efficiencies with tight distributions, perfect optical appearance, and longtime product reliability, AOI systems and in-line monitoring will be deployed more and more.

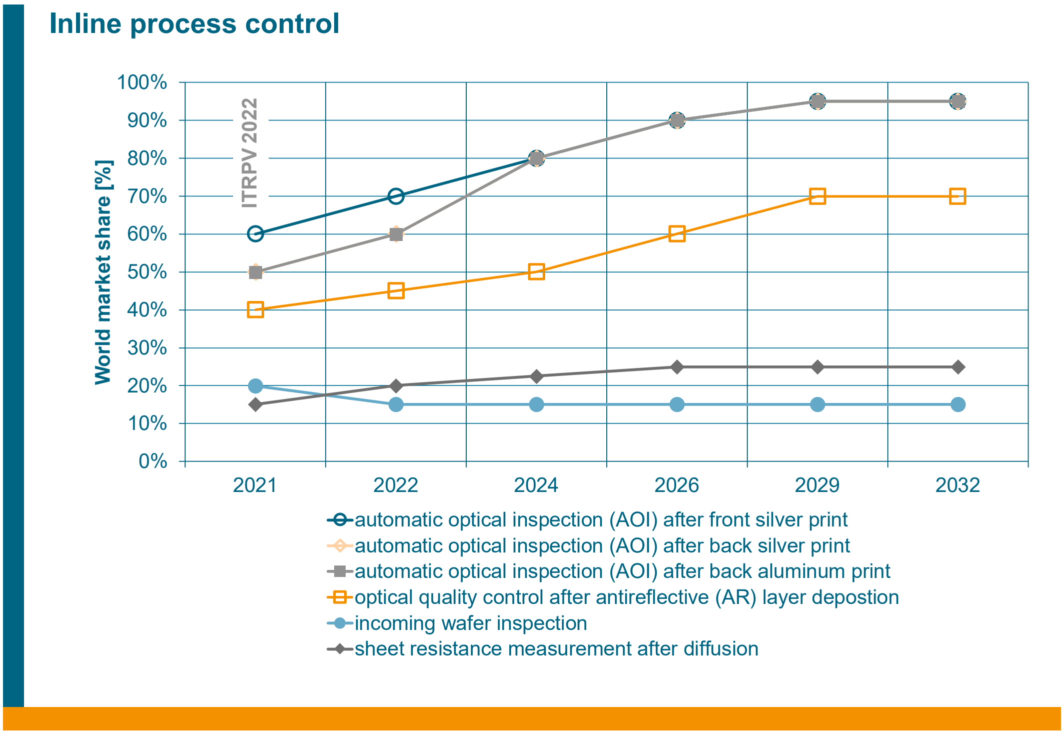


Fig. 64: Market share of inline process control for incoming wafer quality, sheet resistance, antireflective layer deposition, and for printing quality at rear and front side printing.

Fig. 65 shows that AOI (Automated Optical Inspection) is completely used in cell test and sorting. AOI including front side color inspection at cell test is standard in cell production lines with close to 100% in 2022.

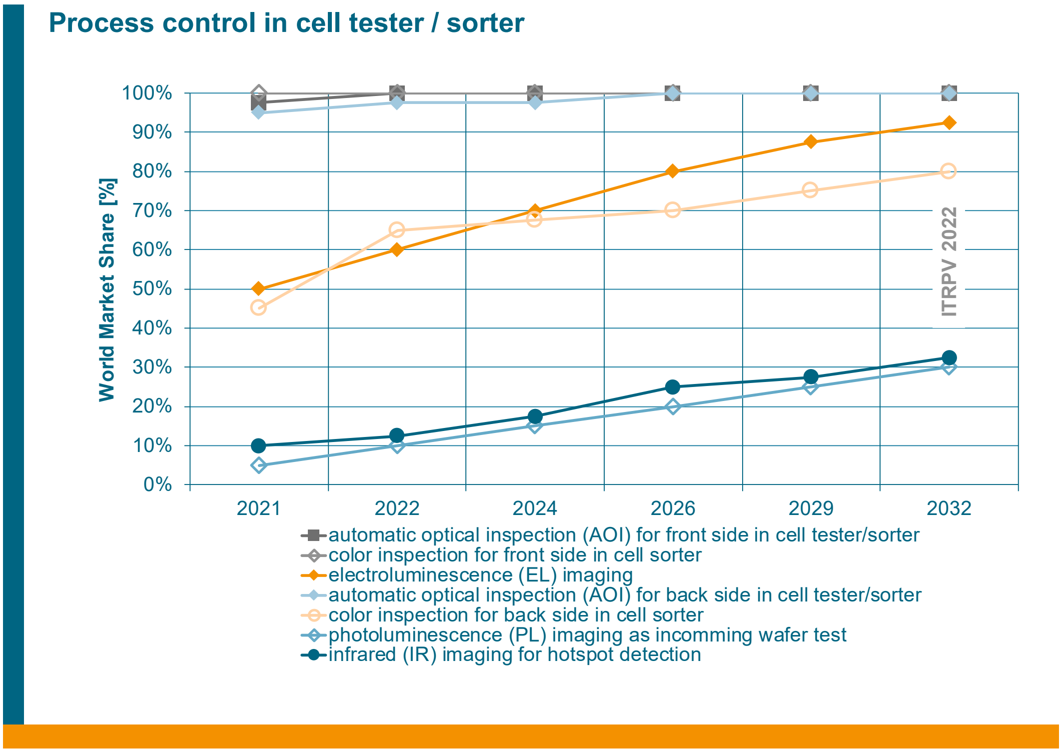


Fig. 65: Market share of different inline Automated Optical Inspection (AOI) systems for process control at cell test.

In addition, we see an increasing share of rear side color inspection for bifacial cells and increasing deployment of EL, IR, and PL imaging systems. The latter are considered to have the lowest implementation share with ≈10% in 2022. Nevertheless, we see a further increasing implementation for the years to come.

The trends for inline testing and manufacturing execution systems (MES) in module production lines are summarized in Fig. 66. EL inspection of modules is standard today. A similar trend is visible in AOI of cells in the stringer process. IR and cell color inspection in the stringer in module production are expected stay on low levels as those inspections are already done at cell test. AOI after lamination will not exceed 50% in the future.

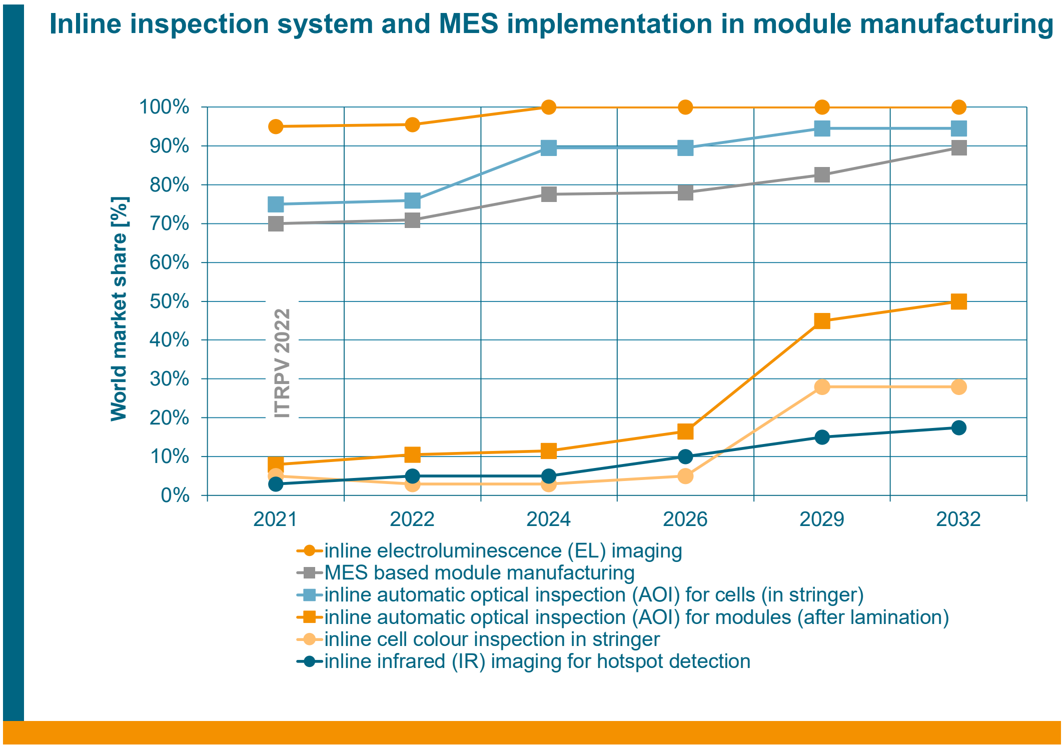


Fig. 66: Trends of inline inspection systems and MES implementation in module production lines.

The implementation of MES progresses - 2022 share of 70% will increase systematically to about 90% within the next 10 years. This is a clear sign towards further automation and smart manufacturing in c-Si module production.

9. Results of 2021 | System

9.1. Components

Module and balance of system (BOS) installation costs are the largest contributors to PV levelized cost of electricity (LCOE). The global average costs for these items increased slightly in 2021 due to supply chain constraints, materials price increases, and other inflationary pressures. If higher capital costs pressures persist, lower LCOE would need to come from improvements in product performance and warranty and lower degradation rate over a longer operational lifetime. Improvements in energy yield, lower operations, and maintenance (O&M) expenses, lower financing rates, and local incentives can also work to lower LCOE.

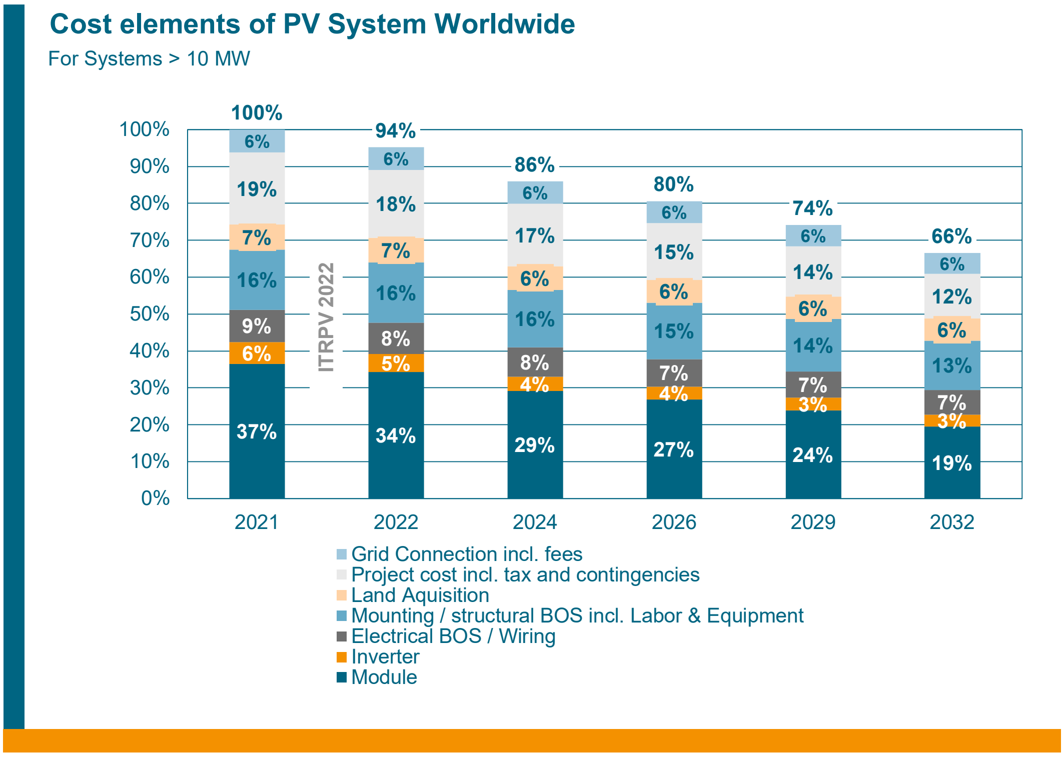


Fig. 67: Relative system cost development for systems > 100 kW Worldwide (2021 = 100%).

Fig. 67 shows the expected trend for system cost and of the corresponding system cost elements for large systems > 100 kWp. We considered the average trend for systems in three regions: Europe, Asia, and the US.

About 35% total PV system cost reduction is expected within the next 10 years due to ongoing technology improvements. The global average price for modules is projected to drop from around \$0.30/W in 2021 to \$0.15/W in 2032, and the global average price for inverters is projected to drop from around \$0.05/W in 2021 to \$0.025/W in 2032. The approximately 25 percent cost reductions projected for the other system components including electrical and structural balance of system (BOS), land, overhead and grid connection are lower than the approximately 50 percent reductions projected for module and inverter. Inflation over the next ten years may cause actual prices to be higher than these 2021 currency benchmarks.

9.2. LCOE Calculation Section

The levelized cost of electricity (LCOE) is a commonly recognized economic metric for comparing the relative costs of different renewable and non-renewable electricity generation technologies. Along with the system capital cost and the solar insolation level, LCOE is also dependent upon operations and maintenance (O&M) expenses, the project financing structure, the expected rates of return for debt and equity stakeholders, national and local incentives, and the usable service life of the system. We have used NREL's System Advisor Model (SAM) discounted cash flow structure to calculate 2021 benchmark and future scenarios of PV LCOE for large PV systems under different insolation conditions (see Fig. 68) [33,34,35].

The ITRPV results for this year again reflect that PV system capital costs vary significantly by continent. The results are 740 USD/kW-dc median capital cost for utility-scale systems in the EU, 650 USD/kW-dc median capital cost for utility-scale systems in Asia, and 980 USD/kW-dc median capital cost for utility-scale systems in the United States. The so-called 'soft costs' including project developer overhead and profit, sales tax, and permitting fees typically have the greatest variance across the globe and from project-to-project. 2021 utility-scale PV system soft costs and module costs in the United States were, respectively, around $0.15/W-dc and $0.07/W-dc higher than the average costs for the EU and Asia. The worldwide average utility-scale system cost trends in Fig. 68 reflect declines from 790 USD/kW-dc in 2021 to around 520 USD/kW-dc in 2032.

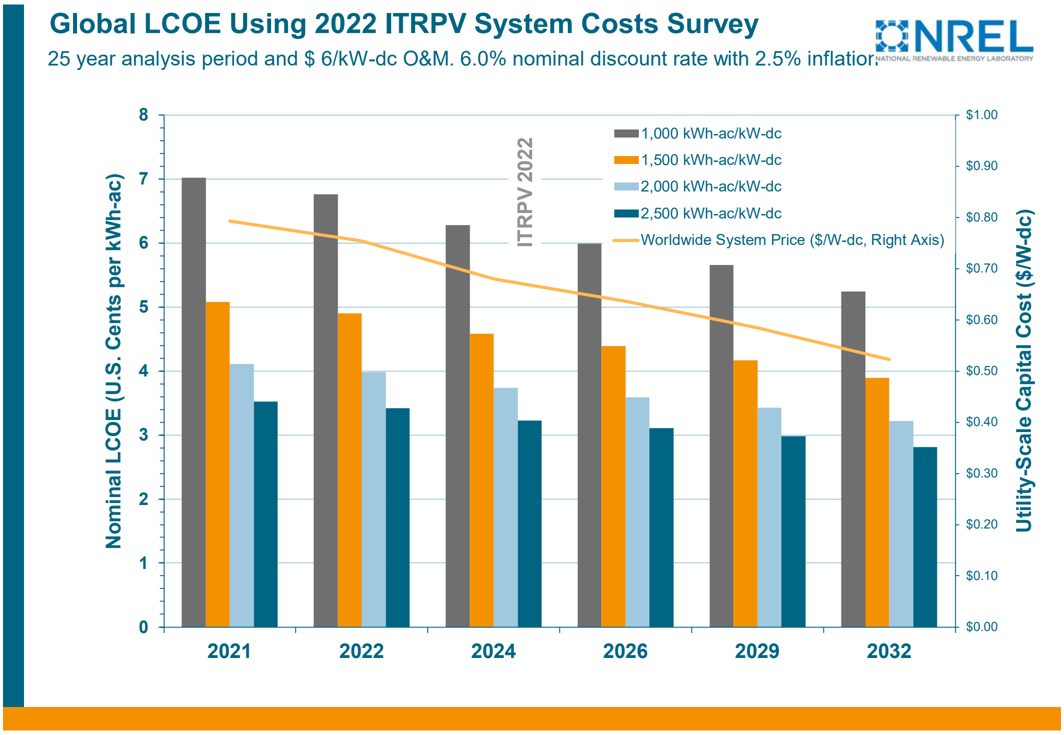


Fig. 68: Calculated LCOE values for different insolation conditions and capital costs projections from the ITRPV.

Using the worldwide average costs for 2021, nominal LCOE values between 3.5 and 7.0 cents per kWh-ac are calculated across the range of solar insolation levels. Using the system capital trends from this year's ITRPV survey, nominal and unsubsidized LCOE is calculated to be between 2.8 to 5.2 U.S. cents per kWh-ac in the year 2032 from the high (2,500 kWh-ac/kW-dc) to low (1,000 kWh-ac/kW-dc) insolation conditions. Improvements in product reliability and energy yield, lower operations and maintenance (O&M) expenses, increases in system voltages and better power electronics, national and local incentives, and increased use of 1-axis tracking systems are all potential opportunities to further reduce LCOE.

For our calculations we have assumed 25 years of usable system service life; however, it is expected that advances in module and BOS technology as outlined in the ITRPV could extend service lifetime to even longer. Advances in longer system service life and lower degradation rate would make it possible to lower LCOE even further and help PV become more cost-competitive on a complete lifecycle basis.

10. Outlook

10.1. PV learning curve

Chapter 3 reviews the learning curve status. Fig. 1 shows the price learning curve and the calculated price learning rate. The current learning rate is calculated to 24.1% using all historic price data points from 1979 to 2020. However, considering only the data points from 2006 - 2021, the learning rate raises to 39.5% as shown in Fig. 69.

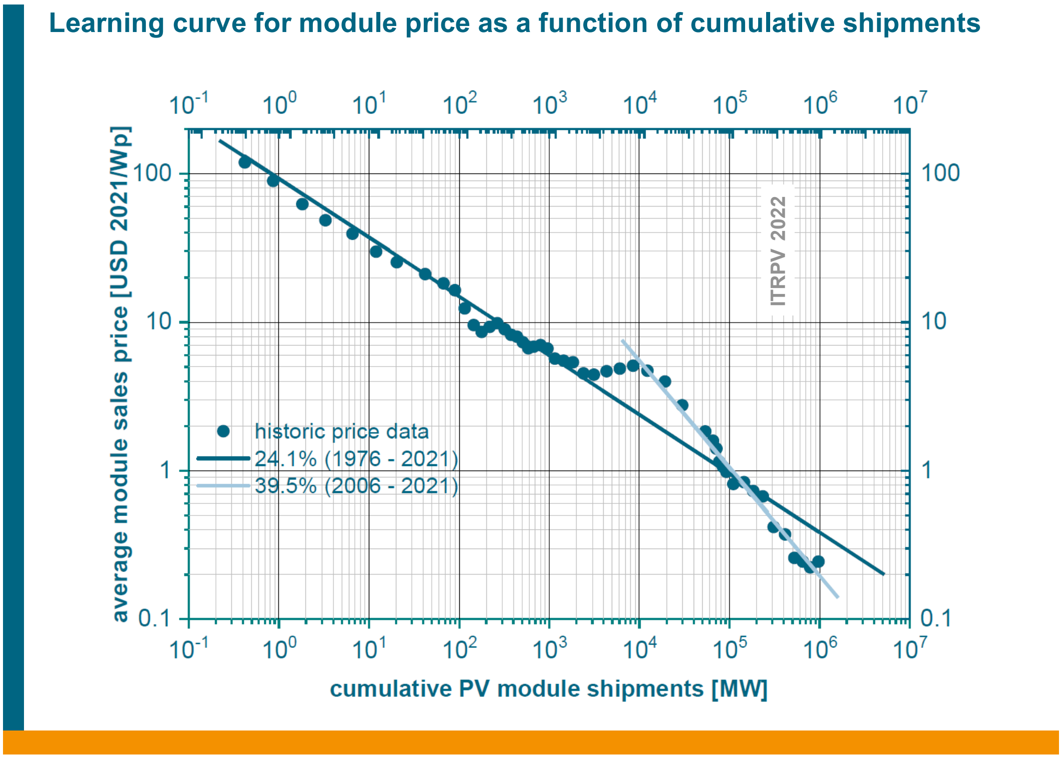


Fig. 69: Learning curve of module spot market price as a function of cumulative PV module shipments and calculated learning rates for the period 1979 to 2021 and 2006 to 2021, respectively.

2006 was the last year of a longer period of silicon shortage. It marks the beginning of c-Si PV mass production in China and thereby the entry into a period of continuous capacity extensions after the scarcity situation of polysilicon and PV modules during the period between 2004 and 2006.

Based on the findings in the ITRPV we started in the 8th edition the analysis about the breakdown to the two basic learning contributors - module power learning and reduction of price (cost) per piece learning.

Tab. 1 summarizes average module efficiencies at different years. The price values were taken from the learning curve while module efficiencies between 2010 and 2019 were calculated, based on average module powers of p-type mc-Si and mono-Si modules reported by the ITRPV (3rd to 11th edition, [14]) in combination with a standardized module size of about 1.64 m² for 60 cell modules. The module efficiency of 1980 was found in [47]. Average module efficiencies for PERC modules in 2020 and 2021 are assumed to 20% based on the ITRPV 12th edition and 20.9% according to Fig. 51 respectively.

The trend to larger wafer formats as shown in Fig. 10 results in a variety of new module formats. Until 2019 mainstream module format was 60 full-cells / 120 half-cells [14]. The corresponding averaged module area increased from 1.64 m² to about 1.7 m² [48] and increased to > 1.8m² according to Fig. 53. For 2021 we calculated an average module power to 392 Wp.

Tab. 1: Yearly learning for module efficiency and price per piece based on module price data (2010 = 100%) [10, 11,12], module efficiencies are calculated from ITRPV module power values (3rd to 11th edition) and from [14]; 1980 module power is calculated from the efficiency indicated in [48].

Year over year learning

Year	1980	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
avg. Module power p- type (ITRPV-data)	147.6	241.5	248	253	262	267.5	278.5	287.5	290	302.5	326	375	392
Module efficency 60 cell [%], avg. Mod. area: 1.64 m² [5], 2019: 1.7 m², 2020ff. ITRPV efficiency	9	14.7	15.1	15.4	16.0	16.3	17.0	17.5	17.7	18.4	19.2	20.0	20.9
Module price [$2021]	36.46	1.84	1.14	0.81	0.82	0.73	0.67	0.42	0.37	0.26	0.24	0.22	0.24
relative module price reduction [%]		95.34	37.77	28.84	-2.84	13.21	7.83	37.65	11.08	30.27	5.91	8.63	-9.48
Module price (Wp-increase only) [$2021/Wp]		1.84	1.79	1.76	1.69	1.66	1.59	1.54	1.53	1.47	1.41	1.35	1.29
Module price (cost reduction per piece only) [$2021/Wp]		1.84	1.19	0.90	0.99	0.91	0.92	0.71	0.68	0.63	0.67	0.71	0.79

Fig. 70 shows the plot of Tab. 1 data points for efficiency learning and per piece learning, respectively. The corresponding calculated learning rates of 7.9% for efficiency learning and 17.2% for per piece learning indicate that the main contribution of the price learning arose from per piece reductions. The 2021 price increase to 0.244 $/Wp as discussed in chapter 4, is the reason for the 3% reduction of the per piece learning compared to the calculation in the 12th edition [14].

Learning curve for module price as a function of cumulative shipments

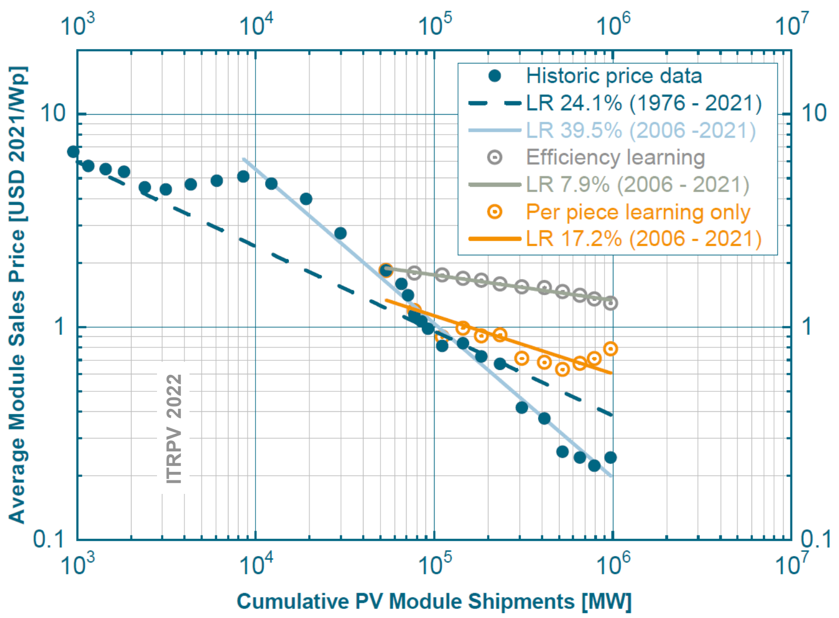


Fig. 70: Log-log plot learning curve of module spot market price as a function of cumulative PV module shipments; update on calculated learning rates for the period 1976 to 2021 and 2006 to 2021 respectively, calculated rates for Wp learning and per piece learning according to Tab. 1.

This emphasizes again that only the combination of efficiency learning, and cost reduction grants the resulting learning despite per piece learnings of the last three years were not in line with former years, mainly due to the introduction of the larger module formats and due to overall cost increases.

Fig. 71 shows the data of Fig. 70 in a linear plot.

Learning curve for module price as a function of cumulative shipments

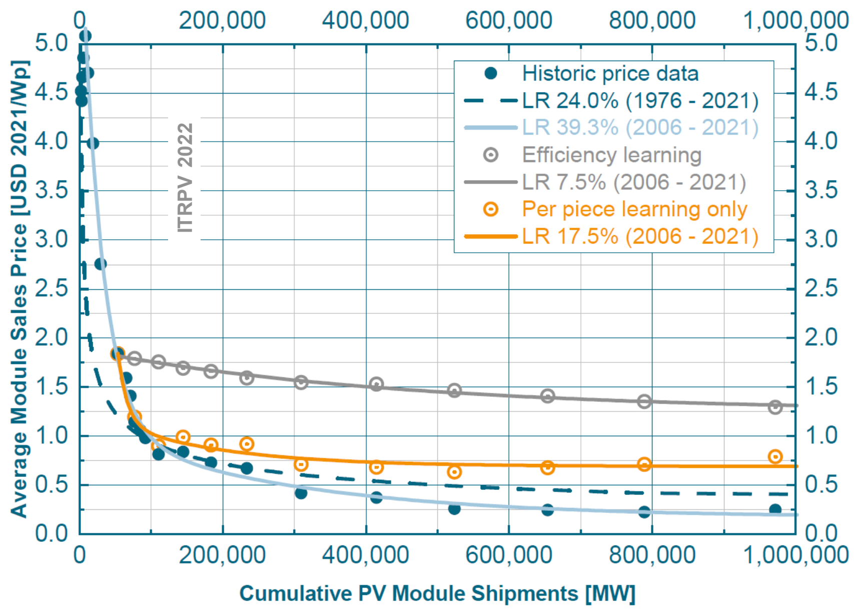


Fig. 71: Linear plot of Fig. 70.

10.2. PV market development considerations

PV will play a key role in a future net zero greenhouse gas emission energy system that has to be installed until 2050 [36]. The most widely publicly discussed PV-related topics and trends are about installed PV module power (DC), module shipments, as well as about PV generated electricity scenarios.

A look at the supplier side, to see the trend of the market for PV modules, cells, wafers, and polysilicon, is less spectacular, but it is essential for investment planning.

The analysis of the annual PV market development until 2050 started in the ITRPV 6th edition. In this 13th edition we continue to discuss the PV contribution in four different scenarios of a global energy system based on up to 100% renewable energy: the scenario of Breyer et. al. [36], the one of Bogdanov et. al [37], the" Green Scenario" of the BNEF NEO2021 [39], and the Sustainable Development Scenario (used for visualizing the regional breakdown) as well as the Net Zero Emission by 2050 scenario of the IEA WEO 2021 [39]. The update of 2021 PV module shipments is considered in the context of this scenarios.

Details of the scenarios and the corresponding considered regions are summarized in Tab. 2.
Fig. 72 - Fig. 75 display these scenarios showing the calculated cumulated PV installation in 5-year steps, the corresponding 5-year average annual PV market without and with replacement after 25 years for the installations until 2025. The historic annual shipments are indicated according to Fig. 1 and Fig. 69.

We consider the following scenarios:

1. Low scenario: (all sectors) — 14.5 TWp installed PV and ≈0.8 TWp avg. annual PV market in 2050, generating 23.5 PWh ≈33% of global electricity generation according to [39].

2. Medium scenario: (all sectors) — 19.8 TWp installed PV and ≈1.1 TWp avg. annual PV market in 2050, generating 39.4 PWh ≈27% of global primary energy demand according to [38].

3. Electricity scenario: (power sector) — 22.0 TWp installed PV and ≈1.4 TWp avg. annual PV market in 2050, generating 38 PWh ≈69% of global electricity [36].

4. Broad electrification: (all sectors) — 63.4 TWp installed PV and ≈4.5 TWp avg. annual PV market in 2050, generating 104 PWh ≈69% of global primary energy demand (including power & heat, transport, and desalination) [37].

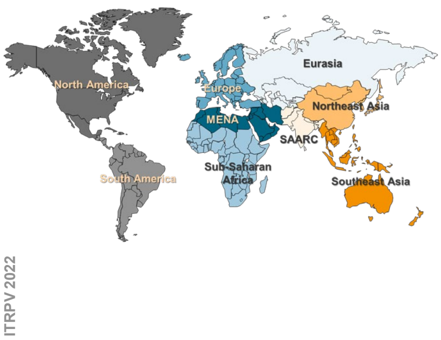
Scenarios 1, 3, and 4 are superimposing calculated results for different world regions.

Fig. 72 illustrates scenario 1 - PV based power generation figures, published in the IEA World Energy Outlook 2021 (WEO 2021), a current analysis about electrical power generation and consumption until 2050, based on assumptions about population growth and energy consumption trends [39]. It considers the limitation of global temperature increase to 1.5°C at the end of the 21st century. This "net zero emission scenario" assumes a PV installation of about 14.5 TWp being enough to cover 33% of global electricity generation in 2050. Energy yield in this scenario is assumed to be about 1.6 kWh/kWp. The average addressable market including replacements after 25 years is calculated to about 770 GWp in 2050.

Tab 2: Summary of reagional results of the different scenarios.

Summary of regional results for the different scenarios

Scenario	Region	Installed power 2050 [TWp]	PV Power generation 2050 [PWh]
Low scenario IEA WEO SDS	Americas	2.0	
	AsiaPacific	6.5	
	ROW	0.1	
	EMEA	2.3	
	total	10.9	17.4
Low Scenario IEA WEO NZE	total	14.5	23.5
Medium scenario primary energy	total	19.8	39.4
Electricity scenario	Sub-Saharan Africa	1.3	
	MENA	1.4	
	North America	2.5	
	Northeast Asia	7.4	
	SAARC	3.7	
	South America	0.8	
	Southeast Asia	2.4	
	Eurasia	0.4	
	Europe	2.0	
	total	22.0	38.1
Broad Electrification	Sub-Saharan Africa	2.9	
	MENA	4.6	
	North America	7.0	
	Northeast Asia	17.8	
	SAARC	11.9	
	South America	2.3	
	Southeast Asia	5.3	
	Eurasia	2.6	
	Europe	8.9	
	total	63.4	104.0



Historic shipments plotted in Fig. 72 are above the corresponding assumed addressable market of this scenario. WEO 2021 is still underestimating the market potential of PV installations from our point of view.

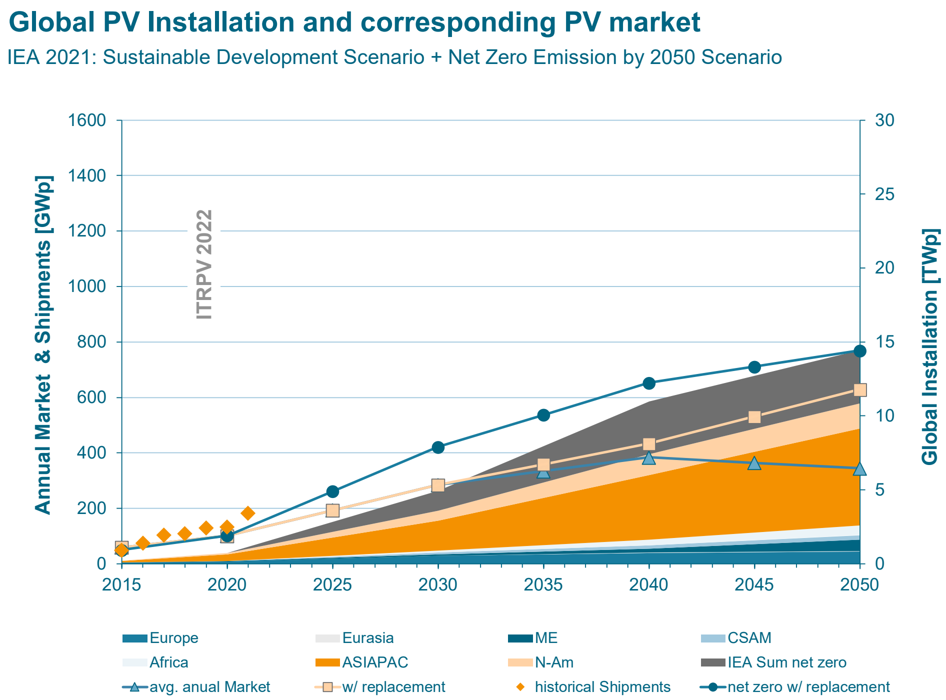


Fig. 72: Scenario 1 – low scenario: annual PV market and corresponding cummulated global installation of 14.5 TWp installed PV in 2050 including replacements after 25 years, acording to [38].

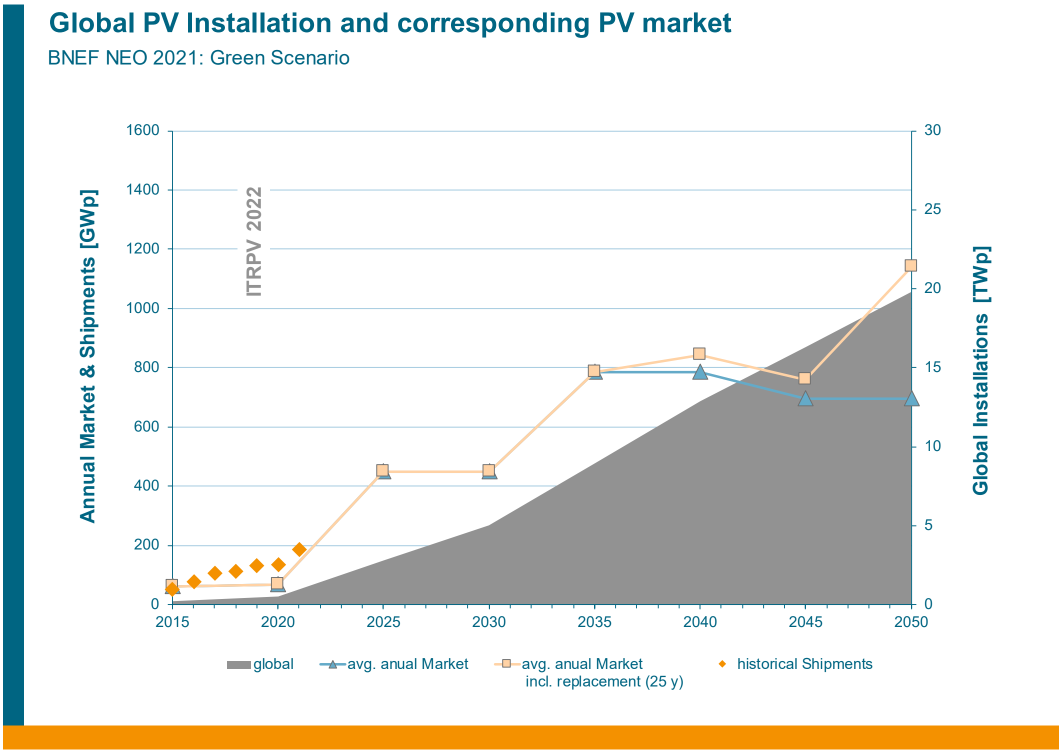


Fig. 73: Scenario 2 – medium scenario: annual PV market and corresponding cummulated global installation of 19.8 TWp installed PV in 2050 including replacements after 25 years, acording to [38].

Fig. 73 shows the updated BNEF NEO 2021 scenario. In 2050 19.8 GWp installed PV are assumed in this scenario, sufficient for 39.4 PWh of energy that will cover about 27% of primary energy consumption in 2050, about 3 times more than in a corresponding 2017 report discussed in ITRPV 10th edition [40]. The annual PV market including replacements after 25 years of operation in this scenario is assumed to 1.14 TWp in 2050. This scenario assumes a significant market increase is assumed after 2020 to a five-year average of more than 400GWp until 2030 and about 800 GWp afterwards. The historic shipments until 2021 are still close to the assumption. This scenario is significant more optimistic than earlier BNEF assumptions: close to three times of the assumption of the BNEF NEO 2020, discussed in the 12th edition.

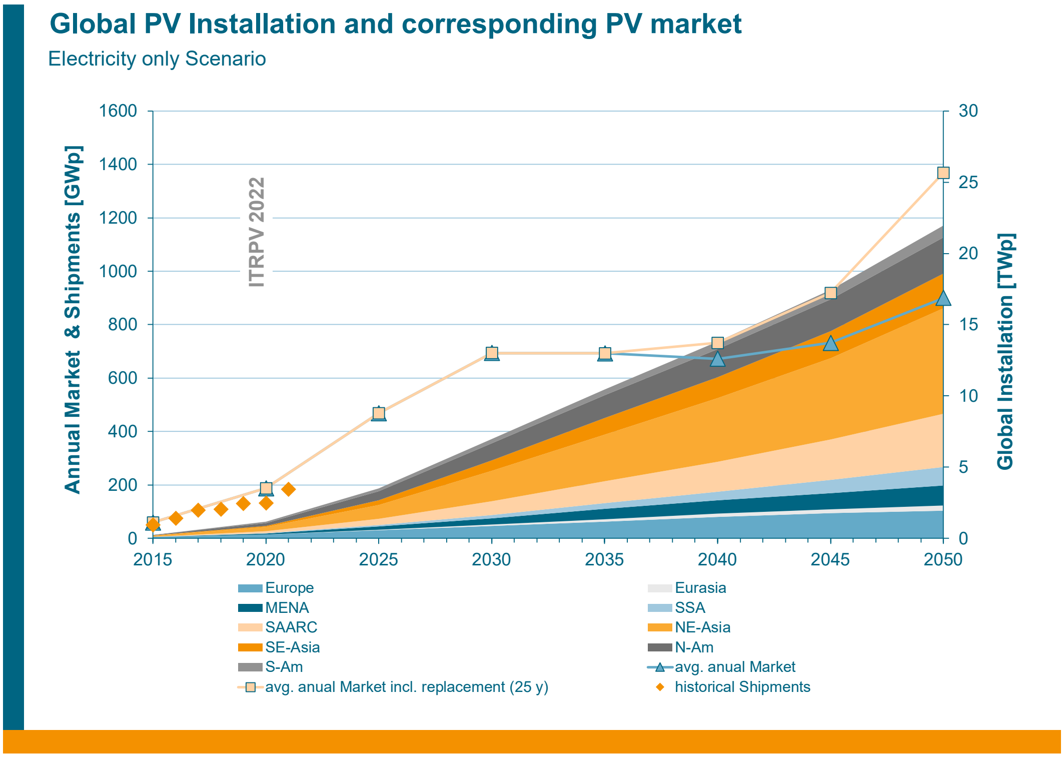


Fig. 74: Scenario 3: Cumulative installed PV module power and 5-year average annual market for global PV module installation of 22.0 TWp in 2050 (see Tab. 2 and [36]).

Scenarios 3 and 4 consider the need of a net zero greenhouse gas emission energy system no later than 2050. PV will be the key technology to reach a 100% renewable energy and greenhouse gas emission free energy economy by 2050, considering the three main energy consumption field of power & heat, transportation, and desalination for 9 major global regions as summarized in Tab. 2, a model presented in [37] and [41] is used.

The Electricity scenario shown in Fig. 74 considers the contribution of PV in a 100% renewable energy-based power sector [33]. The 22.0 TWp will generate approximately 38.1 PWh in 2050.

Fig. 75 shows the required PV installation trend to reach the Broad electrification scenario 4. This will be the path towards a zero-greenhouse gas emission economy in 2050.

Scenarios 3 and 4 consider an average system energy yield of approximately 1730 kWh/kWp and 1650 kWh/kWp respectively realized by power plant installations in higher insolation regions, also taking single axis tracking with higher yields into account.

It is remarkable that the historic shipments are quite close to the required shipments in both scenarios.

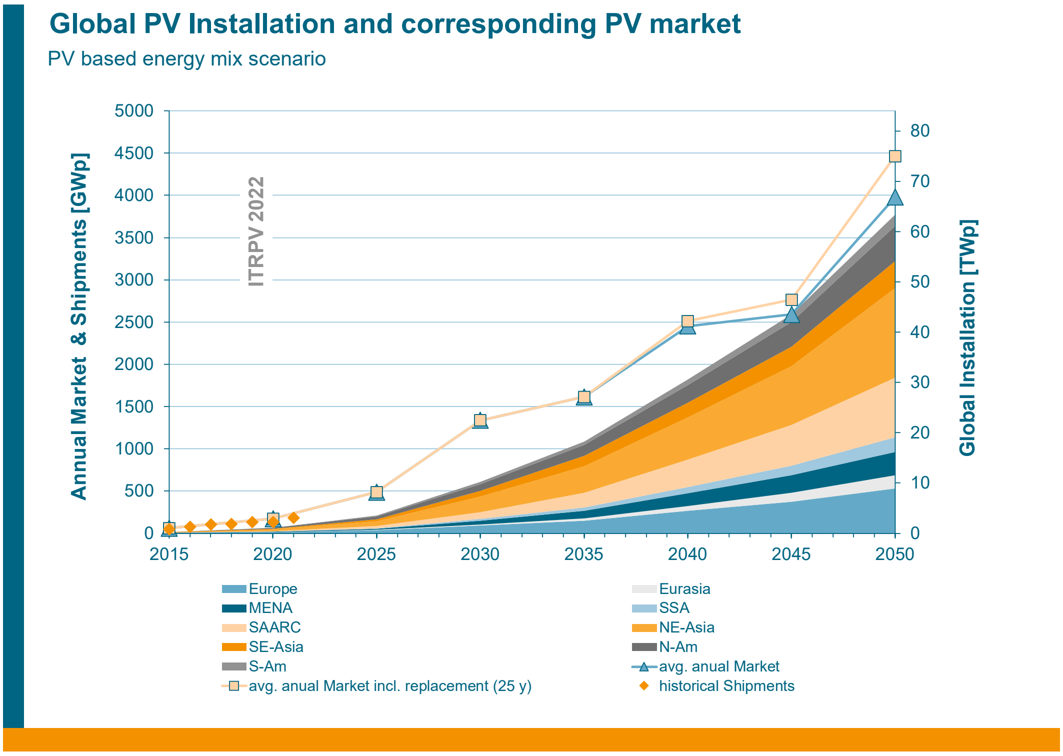


Fig. 75: Scenario 4: Cumulative installed PV module power and 5-year average annual market for global PV module installation of 63.4 TWp in 2050 in a zero greenhouse gas emission economy - broad electrification (see Tab. 2 and [37]).

All four scenarios show that there will be a formidable and increasing module market in the future. Production capacity is increasing continuously. The risk of volatile market situations as seen in 2021 and discussed in chapter 1 are permanently present.

A continues increasing PV module demand is fuelled by the fact that PV electricity is about to become the cheapest source of electricity globally. Cheap PV electricity will drive power-to-X demand so that other energy sectors can also benefit from low-cost PV. Scenario 4 assumes a broad electrification for fulfilling the targets of the Paris Agreement for a least cost energy system.

Scenario 1 will be no challenge for the PV industry. Module capacity is forecasted to have reached 470GW in 2021. So, 800 GW markets will be served even within the next years with existing technologies. Production capacities of above 1TWp as discussed in Scenarios 2 and 3 seem to be manageable even with today's mainstream technologies. Production capacities significant beyond 1 TWp appear more challenging also regarding material consumption [42]. Beside the expected increase of PV installation and production, recycling needs will become more important in the future - as business opportunity and as challenge [43, 44, 45].

Improved tool concepts in cell manufacturing for production lines with matched throughput between front and backend, as discussed in chapter 6.2, will support future production capacity increase. Anyhow, a capacity increase beyond the 1 TWp level will require further improved production technologies. PV equipment suppliers have to support the installation of new production capacities, capable of processing all large wafer formats from M6 to G12. Upgrades for existing production capacities to larger wafer formats should be supported as much as economically feasible. New c-Si capacities for cell and module will deploy mature PERC concepts but should be upgradable. Upcoming n-type cell technologies should be considered as possible upgrades especially in the case of TOPCon and for c-Si based Tandem concepts. Completely new fab capacities from the beginning have to be considered for SHJ as discussed in 6.3.

The continued support of depreciated production lines, the replacement of worn-out equipment and the support of upcoming capacity expansions with smart factory approaches as discussed in chapter 8. will constitute considerable business segments in the future. All these facts emphasize the positive outlook for the whole c-Si PV industry.

The current ITRPV edition discussed possible trends and improvements in c-Si PV technology like increasing cell and module efficiency, increasing module power, more efficient usage of poly-Si and all non-Si materials as well as a higher utilization of all production capacities. All these measures will help manufacturers in their efforts to supply the market with highly competitive and reliable c-Si PV power generation products in the years to come. The price learning of PV modules will continue, and this will further push the LCOE reduction of PV systems.

10.3. Accuracy of roadmap projections

The ITRPV has been publishing reports since 2010. Since the 1st edition, investigated parameters have been reported as median values of the past year as well as predictions for the current year and the next 10 years to come. The data of the first reported year in each edition are therefore state of the art values of technical parameters and status quo values for others. In [46] we reviewed for the first time the forecast quality of several technical parameters like the amount of remaining silver of a c-Si cell and the as-cut wafer thickness of c-Si wafers. The following figures will visualize the prediction quality of ITRPV trends for some key parameters during the past 12 years.

Saving silver in cell manufacturing is important as silver is the costliest non-silicon material in the c-Si PV value chain and a resource used not only by PV but also by other industries. The dependency on the world market requires continuous reduction of silver consumption. Reduced usage of silver will be mandatory to stay competitive.

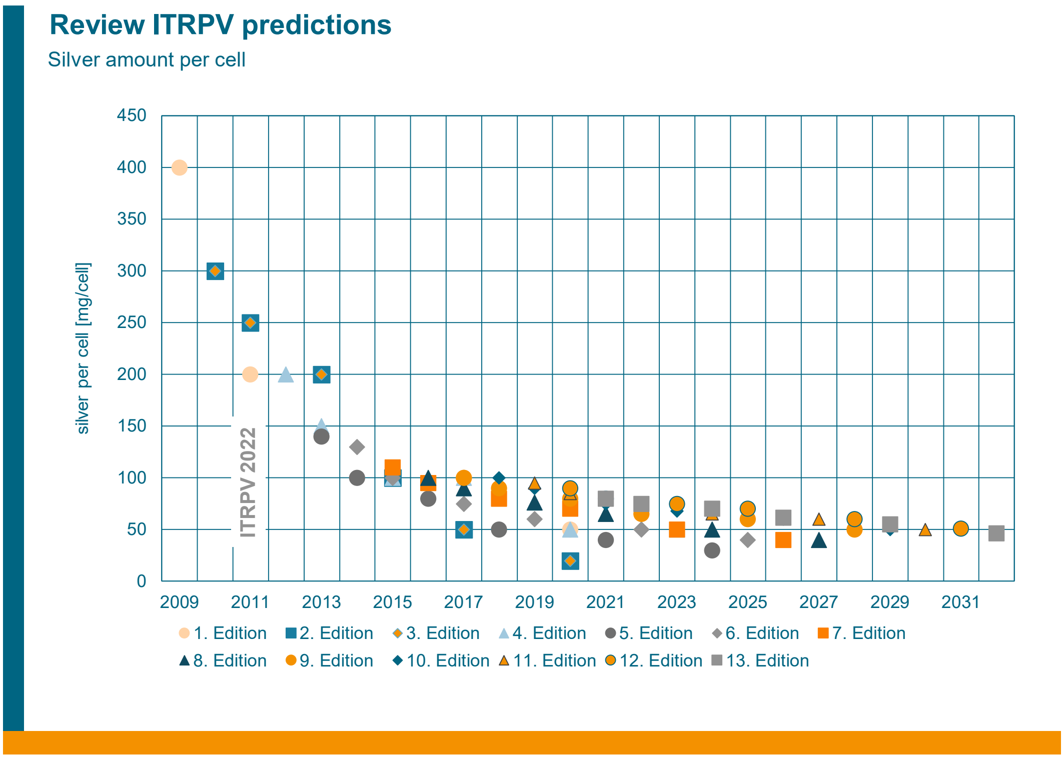


Fig. 76: Predicted trend of remaining silver per monofacial cell concepts using diffused pn junctions - predictions of ITRPV editions.1st – 11th edition is for ≤M2 format, 12th and 13th edition consider M6 format.

Fig. 76 shows that silver reduction - including the data of the 13th edition - has been predicted quite well since the 1st edition. Realizing less than 100 mg of remaining silver took longer than expected, but a further reduction is ongoing.

The data of the 12th and the 13th edition consider M6 wafer format – that's why the trend of the latest editions consider slightly more silver due to the larger wafer area. Former editions considered M0/M2/G1 format.

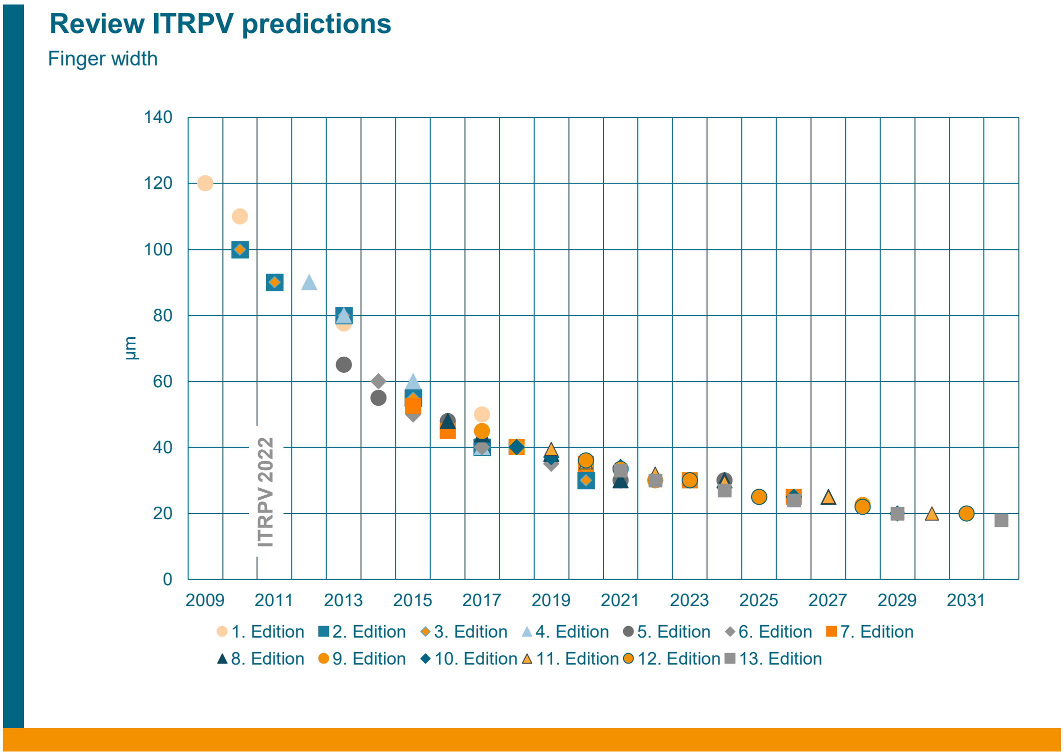


Fig. 77: Predicted trend of finger width at front side print - predictions of ITRPV editions.

The reduction of finger width is key for silver reduction. Fig. 77 shows the prediction of finger width at the cell front side. It can be seen that the reality is following the predictions quite precise. Both trends emphasize that cost saving activities have been consistently continued since the 1st edition in 2010.

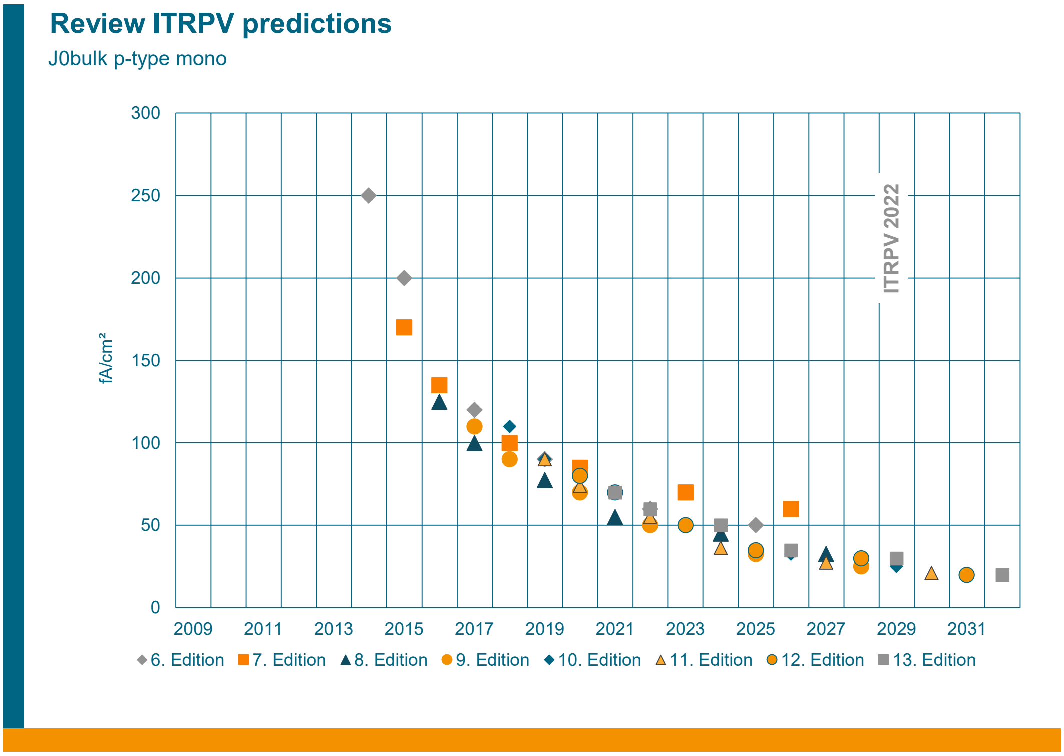


Fig. 78: Predicted trend of J0bulk for p-type mono-Si material - predictions of ITRPV editions.

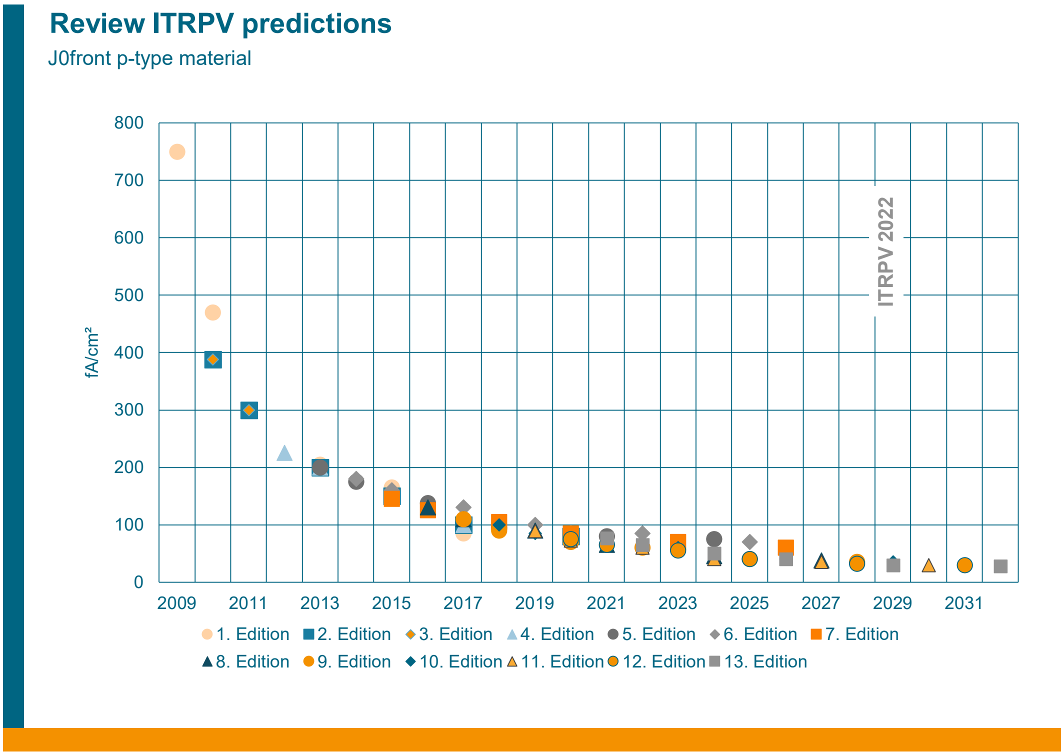


Fig. 79: Predicted trend of J0front for p-type material - predictions of ITRPV editions.

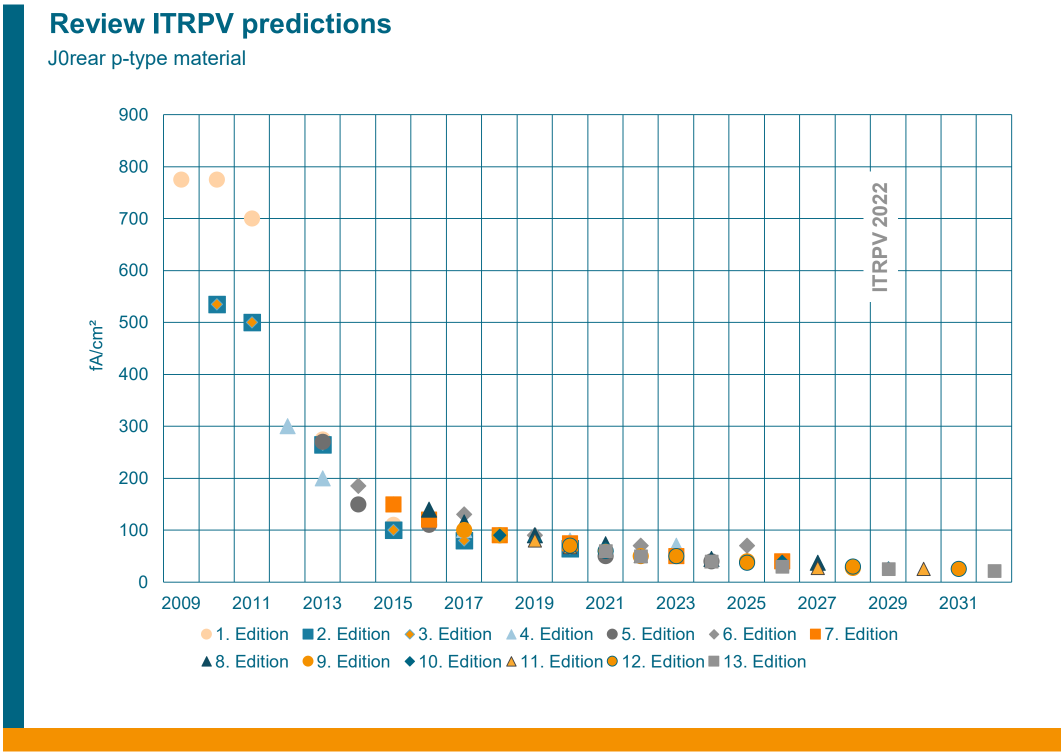


Fig. 80: Predicted trend of J0rear for p-type material - predictions of ITRPV editions.

The improvement of c-Si bulk is key to improve cell efficiency as discussed in chapter 6.2. Fig. 78 shows that the required J0bulk improvements of p-type mono-Si material have been reached quite well.

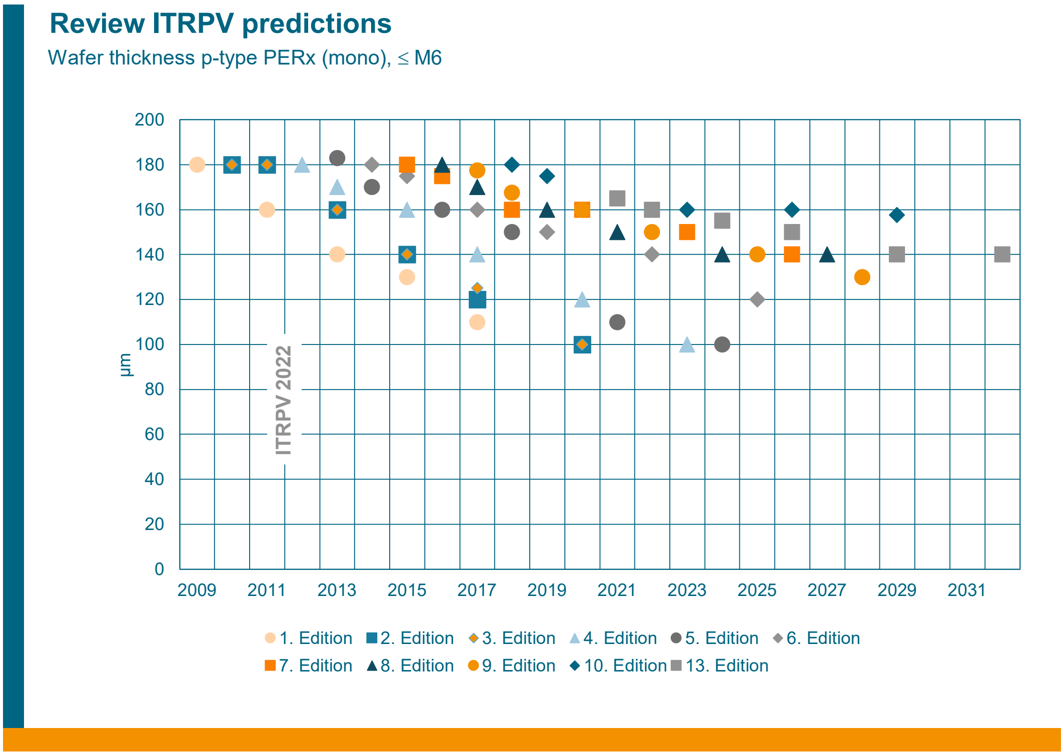


Fig. 81: Predicted trend of p-type mono-Si wafer thickness. 1st- 11th edition thickness or wafers < M6; since the 12th edition thickness for M6 wafer format.

The progress of process improvements on p-type front and rear side are shown in Fig. 79 and Fig. 80. J0front and J0rear of p-type cell concepts improved in line with ITRPV requirements.

In contrast to silver that is used in several industrial applications, poly-Si is a material exclusively produced and mainly used in PV (beside the volume used for the semiconductor industry). Process improvements and resulting capacity expansions enabled significant cost reductions. A significant reduction of silicon consumption in wafer manufacturing was realized by the fast roll out of DWS as discussed in former editions. Nevertheless, cost savings in poly-Si consumption could be realized by wafer thickness reductions; mono-Si wafer thickness was reduced to below 180µm during the last years.

Fig. 81 shows the prediction quality for wafer thickness of mono-Si for p-type BSF and PERx cell concepts. It is clearly visible that the originally anticipated thickness reduction speed was not realized at all. 180 µm remained for a long time the mainstream thickness. In 2022, 160µm are standard in p-type cell manufacturing, a further reduction to about 140µm appears in this trend as a imit.

10.4. Final remarks

We collected all data presented in this ITRPV edition at the end of 2021 from leading companies along the c-Si value chain, international PV manufacturers, PV equipment and material suppliers, PV institutes as well as PV service providers, listed in the Acknowledgment. Plans call for this roadmap to be updated annually. The topics discussed require cooperation along the PV value chain - between tool and material suppliers, PV manufacturers, project developers, EPC companies, end-customers, and institutes. A version of this document for download, as well as information on how to get involved in roadmap activities, can be found at the following website: itrpv.vdma.org.

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